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VELOCITY DISTRIBUTION IN THE WAKE OF BODIES OF REVOLUTION BASED ON DRAG COEFFICIENT

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FOREWORD

This report was prepared by the Department of Aeronautics and Engineering Mechanics of the University of Minnesota in accordance with Air Force Contract Number AF 33(616)-8310 concerning aerodynamic deceleration. The work being accomplished under this contract is jointly sponsored by the QM Research and Engineering Command, Department of the Army; Bureau of Aeronautics and Bureau of Ordnance, Department of the Navy; and Air Force Systems Command, Department of the Air Force, and is directed by a Tri-Service Steering Committee concerned with aerodynamic deceleration. The contract was administered by the Aeronautical Systems Division with Mr. James H. DeWeese of the Retardation and Recovery Branch, Flight Accessories Laboratory, Aeronautical Systems Division, acting as Project Engineer.

Staff members of the University of Minnesota who have contributed to this report include Messrs. R. J. Niccum, E. L. Haak, D. J. Monson, K. J. Goar and a number of students of the University of Minnesota, and the authors wish to express their appreciation to them.

ABSTRACT

A theoretical analysis of the turbulent wake behind a body of revolution has been made, and an equation for the velocity distribution in the wake has been found in terms of four constants which are determined from experiments. Measurements of the velocity distribution in the wake behind twelve bodies of revolution are presented, and the four constants for each body are derived.

A generalization of the empirical constants in terms of body drag coefficient is made. Calculation velocity distributions using the empirical constants compare satisfactorily with measured distributions.

The publication of this report does not constitute approval by the Air Force of the findings or conclusions contained herein. It is published only for the exchange and stimulation of ideas.

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A - constant multiplier of centerline velocity defect law

a - dimensionless constant multiplier of centerline velocity defect law

b - radial width of the wake

C_1, C_2 - constants

C'_1, C'_2 - constants

C_D - drag coefficient

C_P - pressure coefficient

D - diameter of body of revolution

D_1 - aerodynamic drag of body of revolution

K - constant multiplier of wake width law

k'' - dimensionless constant multiplier of wake

l - a mixing length

m - constant exponent of centerline velocity defect law

n - constant exponent of wake width law

R - radius of body of revolution

r - coordinate perpendicular to axis in cylindrical coordinate system

S - projected area of body of revolution

s, s_1, s_2 - constants in exponent of velocity distribution equation

u - velocity defect in wake, defined as difference between free stream velocity and mean velocity in X-direction

u_b - velocity defect at point defined as the boundary of the wake

u_{max} - maximum velocity defect, occurring on centerline

u_{min} - minimum velocity defect, equal to zero

V - disturbed or mean velocity of flow in X-direction

V_b - mean velocity in X-direction at point defined as boundary of the wake

V_{CL} - mean velocity in X-direction on centerline

V_∞ - free stream velocity

v_r - mean velocity of flow in r-direction

v_θ - mean velocity of flow in θ -direction

X - coordinate in direction of free stream velocity

α - half angle of cone

ε - "apparent" or "virtual" kinematic viscosity

η - coefficient of proportionality

η' - dimensionless coefficient of proportionality

θ - coordinate defining angular direction in cylindrical coordinate system

κ - an empirical constant

ρ - density

τ - turbulent shearing stress

SECTION 1
INTRODUCTION

The turbulent wake behind a body in subsonic flow has been the subject of theoretical investigations by several authors (Refs 1,2,3,4). These investigations, which consider both two and three dimensional wakes, are given extensive review in Ref 5.

No mathematically accurate solution has thus far been obtained for the flow field in a wake, and the authors have made assumptions which cause their results to agree with experiments only relatively far downstream from the body. However, in problems of aerodynamic deceleration the velocity and pressure distribution in the wake must be known much closer behind the wake producing body. Prompted by this, in Ref 6, an expression for the flow field behind bodies of revolution was derived in terms of an independent constant which was determined from a knowledge of the pressure at the center of the wake. But since this method was intended to describe primarily the wake of a relatively streamlined body at distances 4 to 6 diameters downstream it did not provide good results at lesser distances, and was particularly unsatisfactory for blunt bodies (Ref 7).

In order to make the theory more applicable for streamlined bodies as well as for blunt, particularly in the region close behind the body, it was suggested that certain classical assumptions usually considered valid far downstream, be replaced by empirical expressions derived from experimental data related to the near base region (Ref 8). In this fashion, Ref 9 derived a method including empirical constants determined from measured velocity distributions in the wake behind bodies of revolution with drag coefficients varying

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from 0.194 to 1.4. This method was very promising and is further pursued in the present study.

In particular this report then presents the development and derivations of empirical relationships of the wake characteristics and their generalization in terms of drag coefficients. Furthermore, the calculated velocity distributions based on the direct and the generalized coefficients are compared with experimental results.

SECTION 2
THEORETICAL VELOCITY DISTRIBUTION

2.1 Coordinate System and Geometry

It is customary in analyzing the turbulent wake behind a body of revolution at rest in a moving fluid to use a cylindrical coordinate system (X, r, Θ) as shown in Fig 1.

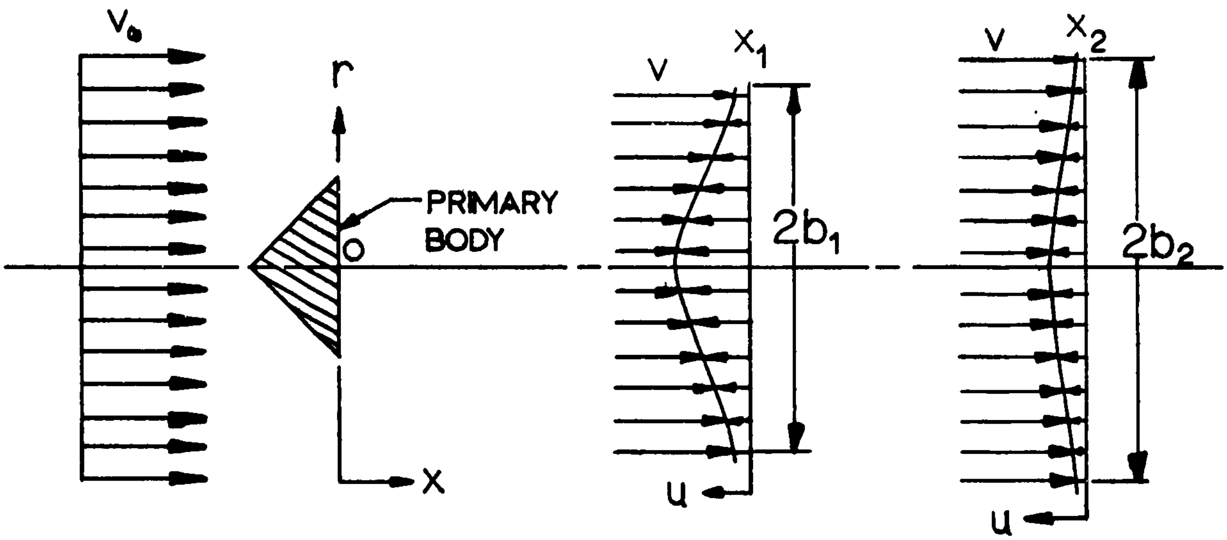

FIG 1. COORDINATE SYSTEM AND VELOCITY DISTRIBUTION BEHIND A BODY OF REVOLUTION

The body is suspended in a uniform flow field of velocity V_∞ with its axis parallel to the direction of flow. The distance X is measured downstream from the base of the body, r is measured perpendicular to the X-axis, and Θ is defined in the usual manner. The mean velocities in the X, r and Θ directions are V, v_r, and v_θ respectively. The difference between the free stream velocity V_∞ and the velocity of the disturbed flow in the wake, V, is the velocity defect u. The radial width of the wake, b, increases with increasing distance downstream, while the velocity defect on the centerline decreases.

2.2 The Equation of Motion

In analysis of boundary layer phenomena, one may assume that the variation of velocity perpendicular to the X-axis is large compared to that along the X-axis, and that the pressure gradient in the X-direction may be neglected. Then assuming constant density, the equation of continuity is

$$\frac{\partial(ru)}{\partial x} + \frac{\partial(rv_r)}{\partial r} = 0 \; . \tag{1}$$

With the further assumption that the laminar shearing stress can be neglected compared to the turbulent shearing stress, which is valid everywhere except near solid boundaries, the differential equation of motion in the X-direction can be written for incompressible flow as

$$\rho\left[V\frac{\partial u}{\partial x} + v_r\frac{\partial u}{\partial r}\right] = \frac{1}{r}\frac{\partial(r\tau)}{\partial r} \quad , \tag{2}$$

where τ represents the turbulent shearing stress, expressed in cartesian coordinates as

$$\tau = \rho\varepsilon\frac{\partial u}{\partial y} \; . \tag{3}$$

There is no exact expression for the "apparent" kinematic viscosity ε ; the expression used in this derivation is Prandtl's hypothesis

$$\varepsilon = \chi\, b(u_{max} - u_{min}) \; , \tag{4}$$

where b is the radial width of the wake and χ is a constant determined by experiment. Introducing Eqns 2 and 3, Eqn 1 becomes

$$V\frac{\partial u}{\partial X} + v_r\frac{\partial u}{\partial r} = \chi\, b\,\frac{1}{r}\frac{\partial}{\partial r}\left[r(u_{max} - u_{min})\frac{\partial u}{\partial r}\right] \; .$$

In the wake, a few diameters downstream, it can be assumed that u and v_r are small compared with V_∞ . Also, $u_{min} = 0$

and u_{max} always occurs on the centerline. Therefore the equation of motion of flow in the wake of a body of revolution is

$$V_\infty \frac{\partial u}{\partial x} = \chi\, b\, u_{max}\left(\frac{1}{r}\frac{\partial u}{\partial r} + \frac{\partial^2 u}{\partial r^2}\right) \quad . \tag{5}$$

2.3 The Solution

In order to obtain a solution of Eqn 5, and in view of Refs 2, 3, and 4, the assumptions are made that the velocity distributions in different cross sections of the wake are similar, and that the wake radial width b and the velocity defect on the centerline u_{max} vary with X according to some power law. These assumptions can be expressed as

$$r = \eta X^n \tag{6}$$

$$b = K X^n \tag{7}$$

$$u = V_\infty \frac{f(\eta)}{X^m} \tag{8}$$

where m and n are unknown constants. To evaluate these constants (Ref 5), the equation of motion, Eqn 2, is written with the assumption that u and v_r are small compared to V_∞, as

$$V_\infty \frac{\partial u}{\partial x} = \frac{1}{r\rho}\frac{\partial (r\tau)}{\partial r} \quad . \tag{9}$$

Employing Prandtl's mixing length hypothesis, $\varepsilon = L^2\left|\frac{du}{dy}\right|$, the turbulent shear stress can be written as

$$\tau = \rho L^2 \left|\frac{du}{dr}\right| \frac{du}{dr} \quad , \tag{10}$$

where L is the mixing length. Utilizing Eqn 8, we obtain:

$$\frac{\partial u}{\partial r} = \frac{V_\infty}{X^m}\frac{\partial}{\partial r}f(\eta) = \frac{V_\infty}{X^m}\frac{\partial \eta}{\partial r}f'(\eta)$$

or:

$$\frac{\partial u}{\partial r} = \frac{V_\infty}{X^{m+n}}f'(\eta)$$

where the superscript (') indicates differentiation with respect to η . Using Prandtl's assumption that the mixing length is proportional to the wake width, yields the relationships (using Eqn 7)

$$L \propto b = KX^n$$

or

$$L \propto X^n \quad .$$

Then from Eqn 10,

$$\tau \propto X^{2n}\left|\frac{V_\infty}{X^{m+n}}f'(\eta)\right|\frac{V_\infty}{X^{m+n}}f'(\eta)$$

or

$$\tau = \text{const}\cdot X^{-2m}\left[f'(\eta)\right]^2 \quad .$$

Differentiation gives

$$\frac{\partial \tau}{\partial r} = \text{const}\cdot 2X^{-(2m+n)}f'(\eta)f''(\eta)$$

so that

$$\frac{1}{r\rho}\frac{\partial(r\tau)}{\partial r} = \frac{\tau}{r\rho} + \frac{1}{\rho}\frac{\partial \tau}{\partial r}$$
$$= \frac{\text{const}\cdot X^{-2m}\left[f'(\eta)\right]^2}{X^n\rho\,\eta} + \frac{\text{const}\cdot 2}{\rho}X^{-(2m+n)}f'(\eta)f''(\eta)$$

or

$$\frac{1}{r\rho}\frac{\partial(r\tau)}{\partial r} \propto X^{-(2m+n)}\left[\frac{\{f'(\eta)\}^2}{\eta} + 2f'(\eta)f''(\eta)\right] \quad . \qquad (11)$$

Similarly,

$$V_\infty \frac{\partial u}{\partial X} \approx V_\infty^2\left[-mX^{-(m+1)}f(\eta) + \frac{1}{X^m} f'(\eta)\frac{-nr}{X^{n+1}}\right]$$

or

$$V_\infty \frac{\partial u}{\partial X} \approx X^{-(m+1)}\left[mf(\eta) + n\eta f'(\eta)\right] \quad . \tag{12}$$

Then using Eqns 11 and 12, Eqn 9 becomes

$$X^{-(m+1)}\left[mf(\eta) + n\eta f'(\eta)\right] \approx X^{-(2m+n)}\left[\frac{[f'(\eta)]^2}{\eta} + 2f'(\eta)f''(\eta)\right] \cdot$$

For both sides of this equation to be of the same order of X requires that

$$X^{-(m+1)} = X^{-(2m+n)}$$

which gives

$$m + n = 1 \quad . \tag{13}$$

A second relationship between m and n can be obtained from the relationship between aerodynamic drag and the momentum change. If u is assumed to be much smaller than V_∞ , the drag can be expressed as

$$D_1 = 2\pi\rho V_\infty \int_0^\infty u r\, dr = \text{const} \quad \cdot \tag{14}$$

Then using Eqn 8, we have

$$\int_0^\infty \frac{f(\eta)}{X^m}\eta X^n \cdot X^n d\eta = \text{const}$$

or

$$D_1 \approx X^{2n-m} = \text{const} \quad \cdot$$

Therefore

$$2n - m = 0 \quad \cdot \tag{15}$$

Now combining Eqns 13 and 15 yields

$$m = 2/3$$
$$n = 1/3 \ .$$

These values are the same as those found by Swain and Schlichting using a different approach. We may now write Eqns 6, 7, and 8 as

$$r = \eta X^{1/3} \tag{6a}$$

$$b = K X^{1/3} \tag{7a}$$

$$u = V_\infty \frac{f(\eta)}{X^{2/3}} \ . \tag{8a}$$

It is now possible to write a solution of the differential equation of motion (Eqn 5) using Eqns 6a, 7a, and 8a. This solution is assumed to be of the form

$$u = u_{max} e^{s\eta^2} \ , \tag{16}$$

where

$$u_{max} = \frac{AV_\infty}{X^{2/3}} \ , \tag{17}$$

and s is an unknown constant. To evaluate this constant s, the values of the terms of the differential equation of motion (Eqn 5) are determined as:

$$V_\infty \frac{\partial u}{\partial X} = -\frac{2}{3} \frac{AV_\infty^2}{X^{5/3}} (1 + s\eta^2) e^{s\eta^2} \ ,$$

$$\frac{1}{r} \frac{\partial u}{\partial r} = \frac{2AV_\infty S}{X^{4/3}} e^{s\eta^2}$$

and

$$\frac{\partial^2 u}{\partial r^2} = \frac{2AV_\infty s}{X^{4/3}} (1 + 2s\eta^2) e^{s\eta^2} \ .$$

Substituting these expressions into the differential equation of motion, we have

$$(1+s\eta^2)(1+6\aleph KAs) = 0 \tag{18}$$

from which we obtain

$$s_1 = -\frac{1}{\eta^2}$$
$$s_2 = -\frac{1}{6\aleph KA} \quad .$$

The solution (Eqn 16) of the differential equation of motion may now be written as

$$u = \frac{AV_\infty}{X^{2/3}}\left[C_1 e^{-\frac{\eta^2}{6\aleph KA}} + C_2 e^{-1}\right] \quad .$$

To determine the constants C_1 and C_2, we use the boundary conditions for the wake;

a) $u=0$ for $r=\eta=\infty$

b) $u=u_{max}$ for $r=\eta=0$.

The constants are thus determined;

$$C_1 = 1,$$
$$C_2 = 0.$$

Therefore the velocity has the Gaussian distribution

$$u = \frac{AV_\infty}{X^{2/3}} e^{-\frac{\eta^2}{6\aleph KA}} \quad . \tag{19}$$

We can now substitute Eqn 6a back into this expression and obtain

$$u = \frac{A V_\infty}{X^{2/3}} e^{-\frac{r^2}{6 \aleph K A X^{2/3}}} .$$

Or, making this expression dimensionless gives,

$$\frac{u}{V_\infty} = \frac{A'}{(X/D)^{2/3}} e^{-\frac{(r/R)^2}{6 \aleph K' A' (X/D)^{2/3}}} . \tag{20}$$

Reference 6 presents expressions for A and K in terms of the drag coefficient C_D and area S of the body and the empirical parameter $\aleph$. The final form of that solution is

$$\frac{u}{V_\infty} = \frac{0.10}{(X/D)^{2/3}} \left[\frac{C_D \pi}{4 \aleph^2}\right]^{1/3} e^{-\frac{0.415 (r/R)^2}{(X/D)^{2/3} (C_D \pi \aleph)^{2/3}}} . \tag{21}$$

2.4 Modification for the Close Body Range

In an attempt to obtain a relationship that expresses the flow field close behind the body ($X/D \geq 4$), it was proposed (Eqn 7a) that the exponent $n = 1/3$ of the wake width law and the exponent $m = 2/3$ of the centerline velocity defect law (Eqn 17) be replaced by empirical values obtained from pertinent experiments.

Again we consider the differential equation of motion, Eqn 5,

$$V_\infty \frac{\partial u}{\partial x} = \aleph b u_{max} \left[\frac{1}{r}\frac{\partial u}{\partial r} + \frac{\partial^2 u}{\partial r^2}\right] . \tag{5}$$

Or, in the dimensionless form, we have

$$\frac{V_\infty}{2} \frac{\partial u}{\partial (X/D)} = \aleph \frac{b}{R} u_{max} \left[\frac{1}{(r/R)} \frac{\partial u}{\partial (r/R)} + \frac{\partial^2 u}{\partial (r/R)^2}\right] . \tag{5a}$$

As in the original theory, the following assumptions are made concerning the wake, with all relations now made dimensionless:

$$\frac{r}{R} = \eta'\left(\frac{X}{D}\right)^{n} \tag{22}$$

$$\frac{b}{R} = k''\left(\frac{X}{D}\right)^{n} \tag{23}$$

$$\frac{u_{max}}{V_\infty} = \frac{a}{(X/D)^{m}} \ . \tag{24}$$

Following the empirical concept we will leave the constants a, k", m, and n arbitrary.

Assuming a solution of the same form as in the original theory (Ref 6) we have

$$u = u_{max}\, e^{s\eta'^2} = \frac{a\, V_\infty}{(X/D)^{m}}\, e^{s\eta'^2} \ . \tag{25}$$

The individual terms of Eqn 5a can now be evaluated as:

$$\frac{\partial u}{\partial (X/D)} = \frac{-a\, V_\infty}{(X/D)^{m+1}}\,(m + 2sn\eta'^2)\, e^{s\eta'^2} ,$$

$$\frac{\partial u}{\partial (r/R)} = 2as\eta' \frac{V_\infty}{(X/D)^{m+n}}\, e^{s\eta'^2} ,$$

and

$$\frac{\partial^2 u}{\partial (r/R)^2} = \frac{2asV_\infty}{(X/D)^{m+2n}}\, e^{s\eta'^2}(1 + 2s\eta'^2) \ .$$

Introducing these relationships into Eqn 5a yields the quadratic solution for

$$\eta'^2 \frac{8\varkappa k''a}{(X/D)^{m+n-1}}\, s^2 + \left[\frac{8\varkappa k''a}{(X/D)^{m+n-1}} + 2n\eta'^2\right] s + m = 0 \ . \tag{26}$$

Employing the quadratic formula, we obtain the rather complicated solutions for s,

$$s_{1,2} = \frac{-\left[\frac{4\varkappa k''a}{(X/D)^{m+n-1}} + n\eta'^2\right] \pm \sqrt{\left[\frac{4\varkappa k''a}{(X/D)^{m+n-1}} + n\eta'^2\right]^2 - 2m\eta'^2 \frac{4\varkappa k''a}{(X/D)^{m+n-1}}}}{2\eta'^2 \frac{4\varkappa k''a}{(X/D)^{m+n-1}}} \ . \qquad (27)$$

It does not seem possible to reduce this expression in order to obtain a practical exponent for the velocity profile. However, by assuming temporarily that m = 2n, the quantity under the radical becomes a perfect square, and we can obtain the much simpler solutions

$$s_1 = -\frac{1}{\frac{4\varkappa k''a}{n(X/D)^{m+n-1}}}$$

and

$$s_2 = -\frac{1}{\eta'^2} \ .$$

Using these results, Eqn 25 becomes

$$u = u_{max}\left[C_1' e^{-\frac{\eta'^2}{\frac{4\varkappa k''a}{n(X/D)^{m+n-1}}}} + C_2' e^{-1}\right] \ .$$

An application of the boundary conditions

a) $u = 0$ for $r = \eta' = \infty$

b) $u = u_{max}$ for $r = \eta' = 0$,

determines the values of the constants C_1 and C_2 to be

$$C_1 = 1,$$

$$C_2 = 0.$$

Thus the velocity distribution in the wake of a body of revolution is expressed by the equation

$$u = u_{max}\, e^{-\frac{\eta'^2}{\frac{4\chi k''a}{n(X/D)^{m+n-1}}}} = \frac{aV_\infty}{(X/D)^m}\, e^{-\frac{\eta'^2}{\frac{4\chi k''a}{n(X/D)^{m+n-1}}}} .$$

Or, introducing Eqn 22, we obtain

$$u = \frac{aV_\infty}{(X/D)^m}\, e^{-\frac{(r/R)^2}{\frac{4\chi k''a}{n}(X/D)^{n-m+1}}} . \qquad (28)$$

Thus, we have obtained a velocity distribution equation with the four constants, m,n,a, and k" left arbitrary. It can be seen that this equation is of the same form as that of the original theory, and in fact, if the values $m = 2/3$ and $n = 1/3$ are substituted into Eqn 28, taking into account the fact that the equation is dimensionless, it is observed that Eqn 28 is identical to Eqn 19.

2.5 The Parameter χ

In Ref 6, the constant χ was determined by experiment so as to force the theoretical and experimental velocity profiles to agree on the centerline. Since in this analysis the constants a, k", m, and n are arbitrary, it is desirable to express χ in terms of these constants. Let the wake boundary be defined as that point where the velocity defect is 10 percent of the local maximum velocity defect, i.e., $(V_\infty - V_b) / (V_\infty - V_{CL}) = u_b/u_{max} = 0.10$. With the constants of the wake width law accordingly determined, we have at the wake boundary (using Eqn 23)

$$u = u_{max}\, e^{-\frac{k''^2(X/D)^{2n}}{\frac{4\chi k''a}{n}(X/D)^{n-m+1}}}$$

or

$$\frac{u_b}{u_{max}} = 0.10 = e^{-\frac{k''^2(X/D)^{2n}}{\frac{4\chi k''a}{n}(X/D)^{n-m+1}}} .$$

This gives

$$\gamma = \frac{nk''(X/D)^{m+n-1}}{9.20\,a} \tag{29}$$

Determination of γ in this manner insures agreement of the theoretical and experimental velocity profiles both at the centerline and at the arbitrary boundary of the wake.

The velocity distribution equation now becomes

$$\frac{u}{V_\infty} = \frac{a}{(X/D)^m}\, e^{-\frac{(r/R)^2}{0.435\,k''^2 (X/D)^{2n}}} \quad . \tag{30}$$

Comparing this relationship with Eqn 21 shows agreement with the solution of Ref 6. With the determination of the arbitrary wake width and centerline defect laws from experiments, Eqn 30 predicts the velocity distribution behind any body of revolution.

SECTION 3
EXPERIMENTS

3.1 Velocity Distribution

Wind tunnel tests have been conducted to determine experimentally the velocity distributions behind the twelve bodies of revolution shown in Fig 2. The details of the experimental procedure and data reduction are presented in Ref 10. Experimental results for the region $2 \leq X/D \leq 20$ are presented in Tables A-1 through A-12, and for the region $2 \leq X/D \leq 16$ are shown in Figs A-1 through A-12 (Appendix). These tabular and graphic results are taken from Ref 8.

3.2 Wake Width

With the wake boundary defined as in previous sections, that is, $u_b/u_{max} = 0.10$, the experimental wake widths b/R were measured for each X/D position for the twelve bodies. These wake boundaries are indicated on Figs A-1 through A-12 (Appendix), and are tabulated in Table 1.

The power law expression of Eqn 22 indicates that these experimental wake widths should plot as straight lines on log-log coordinate paper. Figures A-13 through A-24 (Appendix) present such graphs for each body tested.

It was found that an approximate representation of wake width in the region $2 \leq X/D \leq 20$ could be obtained by assuming a straight line through the experimental wake widths (the one-line approximations of Figs A-13 through A-24, Appendix). The constants k" and n determined from these straight lines (Ref 8) are presented in Table 2. From these figures, it is seen that a one-line approximation is more accurate for the streamlined bodies than for the bluff bodies.

Since the region $2 \leq X/D \leq 8$ is of special interest in problems of aerodynamic deceleration, a better representation behind the bluff bodies, Models B through E, may be

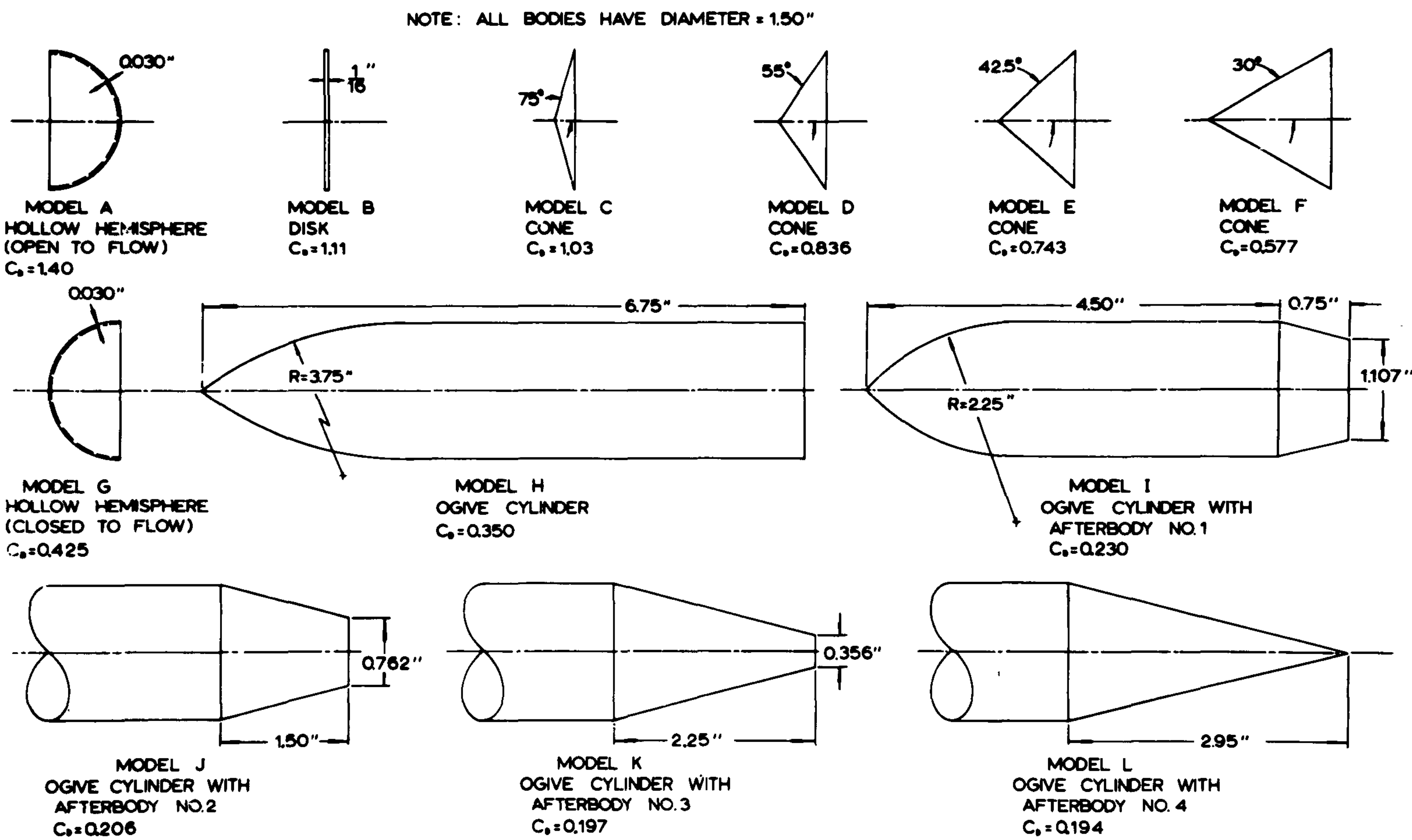

FIG 2. BODIES OF REVOLUTION

TABLE 1. EXPERIMENTAL WAKE WIDTHS

MODEL		X/D=2	4	6	8	10	12	16	20
A	b/R	1.70	2.55	3.50	3.70	4.00	4.50	6.00	6.30
B	b/R	1.88	2.20	2.60	3.05	3.70	4.10	4.60	5.40
C	b/R	1.75	2.25	2.55	2.90	3.40	4.00	4.50	5.00
D	b/R	1.70	2.30	2.60	2.80	3.40	3.80	4.20	4.80
E	b/R	1.70	2.15	2.50	2.80	3.10	3.80	4.60	5.00
F	b/R	1.30	1.85	2.25	2.50	2.80	2.90	3.50	4.20
G	b/R	1.35	1.75	2.25	2.25	2.70	2.90	2.90	3.40
H	b/R	1.10	1.70	2.20	3.00	3.30	3.60	4.30	5.00
I	b/R	1.03	1.20	1.75	1.95	2.00	2.00	2.30	2.50
J	b/R	0.80	0.98	1.65	1.55	1.75	1.85	2.40	2.80
K	b/R	0.72	0.85	1.20	1.40	1.60	1.90	2.20	2.30
L	b/R	0.82	0.90	1.50	1.75	1.70	1.70	2.20	2.50

TABLE 2. EMPIRICAL WAKE WIDTH CONSTANTS

MODEL	$C_{D\infty}$	$2 \leq X/D \leq 20$		$2 \leq X/D \leq 8$		$8 \leq X/D \leq 20$	
		k″	n	k″	n	k″	n
A	1.40	1.14	0.582				
B	1.11	1.26	0.454	1.39	0.368	0.788	0.642
C	1.03	1.33	0.394	1.36	0.365	0.734	0.660
D	0.836	1.34	0.384	1.30	0.384	0.879	0.574
E	0.743	1.32	0.393	1.33	0.358	0.684	0.678
F	0.577	0.927	0.488				
G	0.425	0.985	0.397				
H	0.350	0.693	0.665				
I	0.230	0.810	0.376				
J	0.206	0.541	0.522				
K	0.197	0.493	0.531				
L	0.194	0.565	0.491				

obtained by assuming one straight line approximation in the region $2 \leq X/D \leq 8$ and a second in the region $8 \leq X/D \leq 20$ (the two-line approximations of Figs A-14 through A-17). These constants are also presented in Table 2.

Using the constants from the one-line approximations, the empirical wake widths were calculated for all bodies, and are shown superimposed on the upper halves of Figs A-1 through A-12 (Appendix). It is seen that this approximation is quite accurate for the streamlined bodies, Models F through L, and also for Model A. The wake widths based on the two-line approximations were also calculated, and are shown superimposed on the lower halves of Figs A-2 through A-5; this approximation is seen to be quite satisfactory for these bluff bodies.

3.3 Centerline Velocity Defect

Using the same technique as used in determining the wake widths, the maximum velocity defects for each body have been plotted on log-log coordinate graph paper in order to determine the empirical constants a and m. (The data used in plotting these graphs is presented in Table 3). Again, a one-line approximation for $2 \leq X/D \leq 20$ can be made for all models. However, it is seen that one-line approximations will be accurate for the streamlined models, Models F through L, while for the bluff bodies, Models A through E, the two-line approximation, one for $2 \leq X/D \leq 8$ and a second for $8 \leq X/D \leq 20$, was more accurate. Table 4 presents the constants a and m determined from both the one-line and the two-line approximations. It should be noted that the deviation of the experimental points from the straight line approximations in Figs A-25 through A-36 (Appendix) will be directly reflected in a deviation of the calculated velocity profiles from the experimental ones on the wake centerline.

TABLE 3. CENTERLINE VELOCITY DEFECTS

MODEL		X/D=2	4	6	8	10	12	16	20
A	$\frac{u_{max}}{V_\infty}$		0.25	0.13	0.09	0.08	0.07	0.06	0.05
B	$\frac{u_{max}}{V_\infty}$	1.00	0.31	0.16	0.11	0.09	0.08	0.06	0.05
C	$\frac{u_{max}}{V_\infty}$		0.34	0.15	0.11	0.09	0.08	0.07	0.06
D	$\frac{u_{max}}{V_\infty}$	0.86	0.25	0.14	0.10	0.08	0.07	0.07	0.04
E	$\frac{u_{max}}{V_\infty}$	1.00	0.29	0.14	0.10	0.09	0.07	0.06	0.05
F	$\frac{u_{max}}{V_\infty}$	1.00	0.20	0.12	0.09	0.07	0.06	0.05	0.04
G	$\frac{u_{max}}{V_\infty}$	0.81	0.20	0.13	0.10	0.07	0.07	0.06	0.05
H	$\frac{u_{max}}{V_\infty}$	0.26	0.12	0.10	0.07	0.07	0.06	0.05	0.05
I	$\frac{u_{max}}{V_\infty}$	0.26	0.19	0.14	0.10	0.10	0.08	0.07	0.05
J	$\frac{u_{max}}{V_\infty}$	0.34	0.25	0.12	0.15	0.11	0.10	0.08	0.05
K	$\frac{u_{max}}{V_\infty}$	0.36	0.29	0.17	0.14	0.15	0.12	0.08	0.08
L	$\frac{u_{max}}{V_\infty}$	0.34	0.29	0.12	0.11	0.17	0.10	0.07	0.07

TABLE 4. EMPIRICAL VELOCITY DEFECT CONSTANTS

MODEL	C_{D_∞}	$2 \le X/D \le 20$		$2 \le X/D \le 8$		$8 \le X/D \le 20$	
		a	m	a	m	a	m
A	1.40	0.73	0.93	1.70	1.41	0.34	0.64
B	1.11	1.62	1.21	2.25	1.45	0.66	0.86
C	1.03	1.08	1.02	2.97	1.63	0.32	0.56
D	0.836	1.00	0.84	1.79	1.41	0.39	0.69
E	0.743	0.93	0.73	2.41	1.53	0.48	0.76
F	0.577	0.81	1.03				
G	0.425	0.64	0.87				
H	0.350	0.28	0.61				
I	0.230	0.46	0.70				
J	0.206	0.66	0.79				
K	0.197	0.71	0.76				
L	0.194	0.64	0.74				

3.4 Velocity Profiles

Using the constants a, k", m, and n presented in Tables 2 and 4 (using the two-line approximations where appropriate), velocity profiles were calculated for all models and all X/D positions from Eqn 30. These calculated profiles are shown as the solid curves on Figs A-1 through A-12 (Appendix). It is seen that a very accurate representation of velocity distribution behind all bodies of revolution at all distances downstream greater than X/D = 2 is obtained. In those cases where deviations occur, it is either because the velocity on the centerline deviates from the straight line assumption, or because the experimental velocity profile is not a Gaussian distribution. In the first case, a better fit could be obtained by using the exact value of u_{max} rather than that predicted by the straight line assumption. This method would be similar to the one employed in Ref 6.

SECTION 4
GENERALIZED VELOCITY DISTRIBUTIONS

4.1 Introduction

If the method of determining the velocity distribution in the wake of a body of revolution set forth above is to be useful in predicting the velocity and pressure distribution behind any general body of revolution, it is desirable to be able to predict the values of the empirical constants a, k", m, and n merely from a knowledge of some easily determined parameter of the body, such as its drag coefficient. This should be possible, since one would intuitively expect, for example, a continuously decreasing initial width of the wake with decreasing drag coefficient, corresponding to a continuously decreasing value of the constant k".

4.2 Empirical Constants

Since the values of the empirical constants a, k", m, and n have been determined for bodies with a wide range of drag coefficients, the postulated variations of the wake characteristics should be readily apparent. Furthermore, one may be willing to accept a certain amount of inaccuracy and agree basically to a one-line approximation and plot the constants a, k", m, and n as determined on semi-logarithmic coordinate paper as functions of the drag coefficients (Figs 3 through 6).

Allowing for experimental deviations, one observes that the constants m and n can be assumed to be universal constants in the region $2 \leq X/D \leq 20$. If this range would be reduced to say $4 \leq X/D \leq 10$, the agreement would be even better. The values derived from Figs 3 and 4 are:

$$m = 0.85 \tag{31}$$

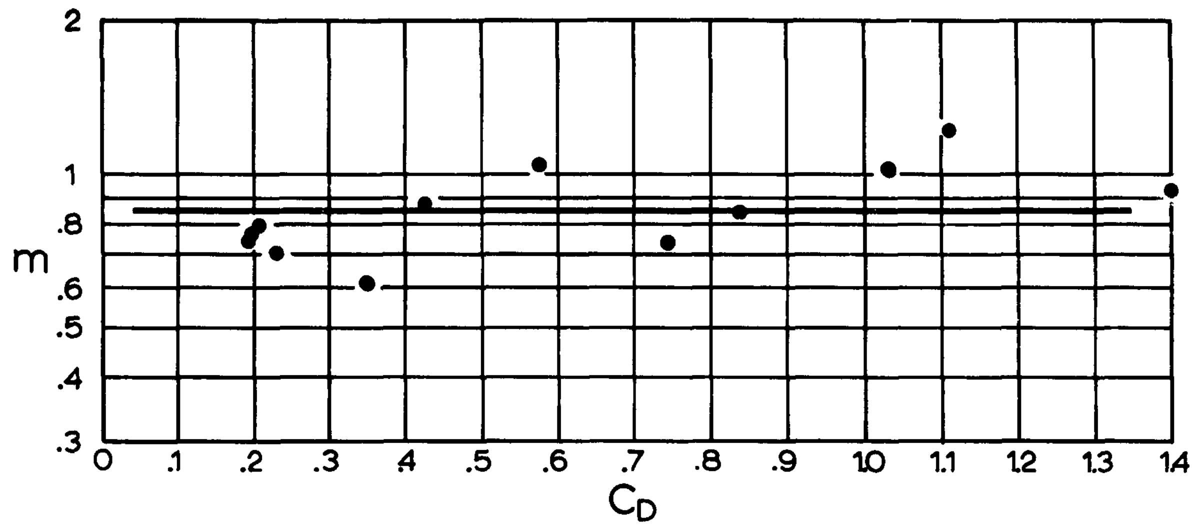

FIG 3. EMPIRICAL CENTERLINE VELOCITY CONSTANT m AS A FUNCTION OF DRAG COEFFICIENT

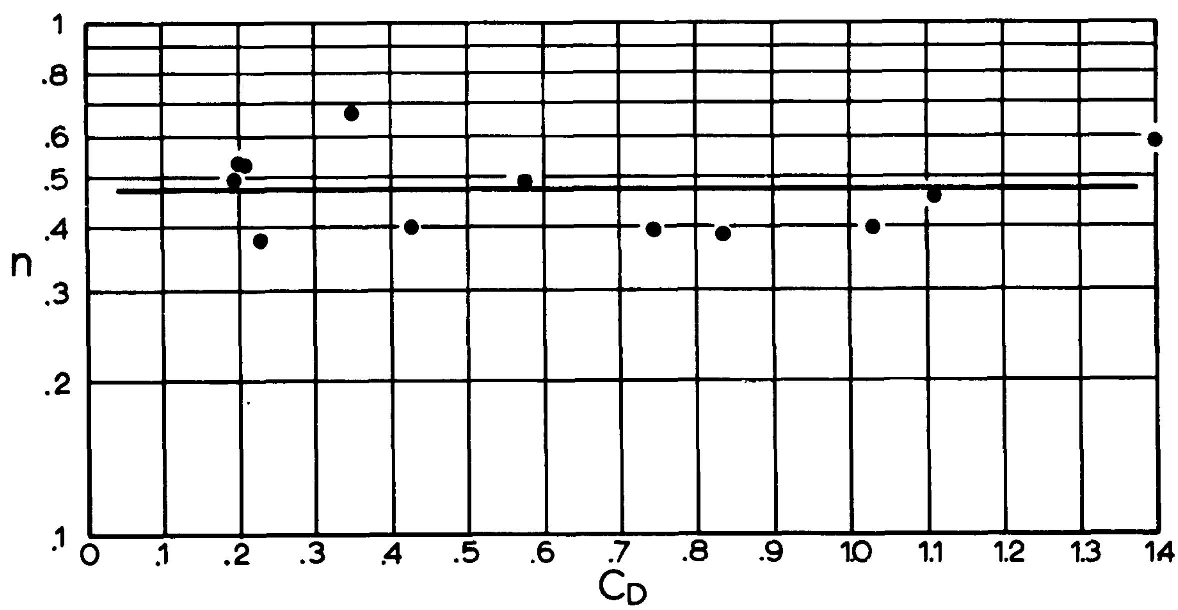

FIG 4. EMPIRICAL WAKE WIDTH CONSTANT n AS A FUNCTION OF DRAG COEFFICIENT

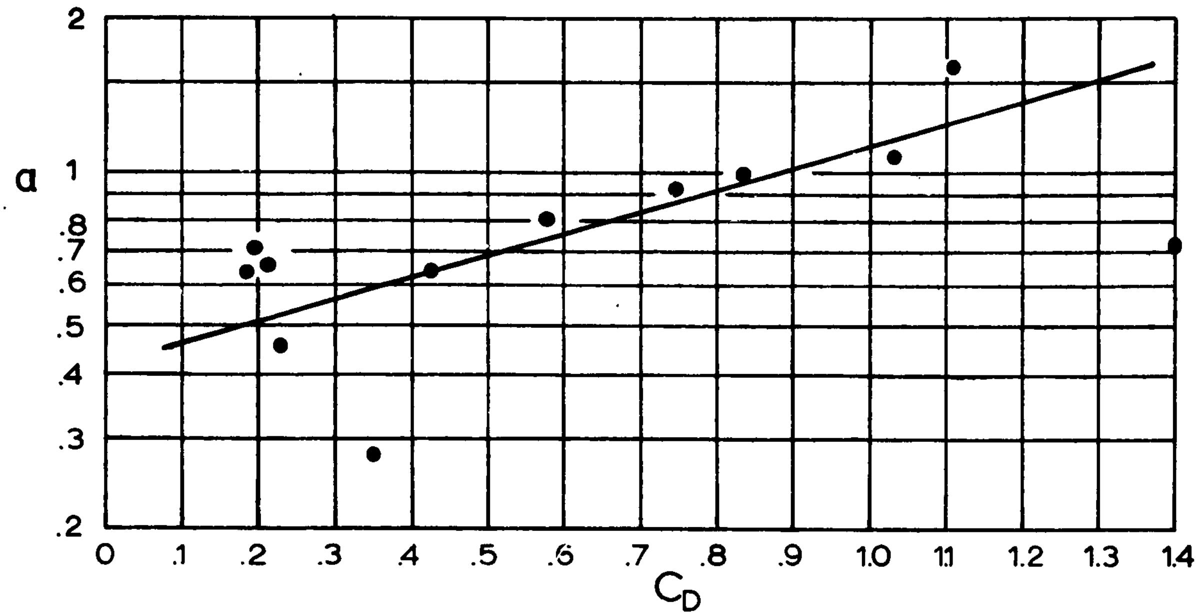

FIG 5. EMPIRICAL CENTERLINE VELOCITY CONSTANT a AS A FUNCTION OF DRAG COEFFICIENT

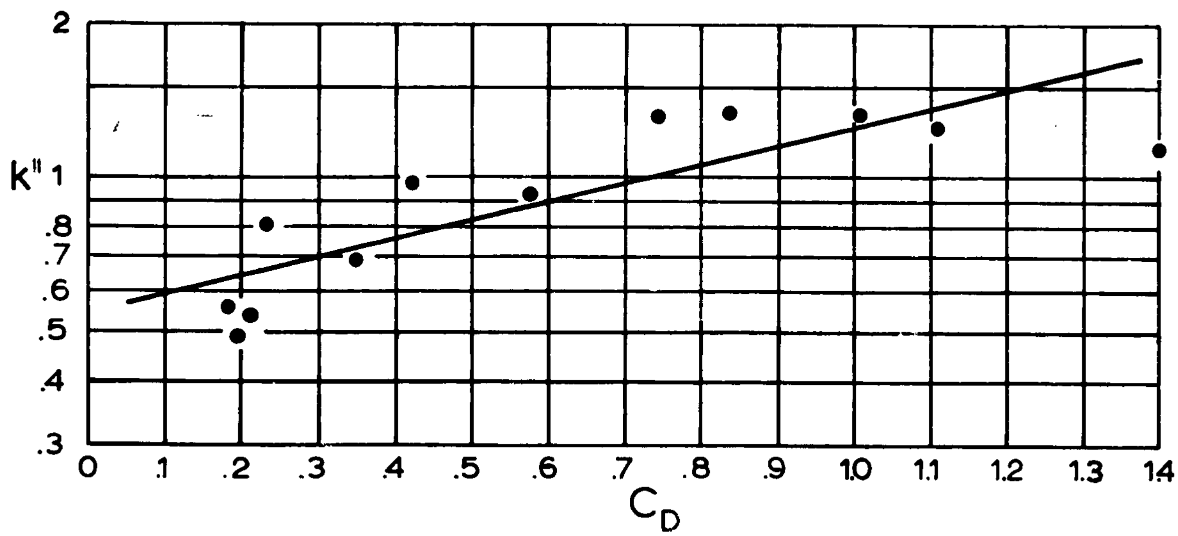

FIG 6. EMPIRICAL WAKE WIDTH CONSTANT k" AS A FUNCTION OF DRAG COEFFICIENT

and

$$n = 0.47 \ . \qquad (32)$$

There is an obvious and significant deviation between these empirical values and the classical values of m and n assumed far downstream to be 2/3 and 1/3 respectively. But, it is also noted, that the assumption $m = 2n$ used in the solution of Eqn 27 is quite accurate.

Evaluating the relationships of Figs 5 and 6, it is found that the functional dependence of the constants a and k" on the drag coefficients in the region $2 \leq X/D \leq 20$ can be expressed as

$$a = 0.42 \ e^{0.99 \ C_D} \qquad (33)$$

and

$$k'' = 0.54 \ e^{0.84 \ C_D} \ . \qquad (34)$$

A comparison between these generalized characteristic values and those given in the Tables 1, 2, 3, and 4 indicates a generally good agreement and one may conclude that the calculated curves in Figs A-1 through A-12 do also represent wake characteristics obtained from the generalized coefficients.

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APPENDIX

TABLES AND FIGURES

TABLE A-1. EXPERIMENTAL VELOCITY DISTRIBUTION IN WAKE OF MODEL A

V/V_∞

r/R	x/D = 2	4	6	8	10	12	16	20
7.67	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
5.67	1.00	1.00	1.00	1.00	1.00	1.00	0.99	0.99
4.67	1.00	1.00	1.00	1.00	1.00	1.00	0.98	0.99
4.00	1.00	1.00	1.00	0.99	0.99	0.99	0.98	0.98
3.33	1.00	1.00	0.99	0.98	0.98	0.98	0.97	0.97
2.67	1.00	0.97	0.96	0.96	0.96	0.96	0.96	0.96
2.00	0.94	0.94	0.93	0.94	0.95	0.94	0.95	0.96
1.33	0.78	0.84	0.88	0.92	0.94	0.93	0.95	0.96
1.07	0.40	0.80	0.88	0.90	0.93	0.93	0.95	0.96
0.80	0.26	0.79	0.87	0.91	0.93	0.93	0.94	0.95
0.53	0.14	0.77	0.87	0.91	0.94	0.93	0.94	0.95
0.27	—	0.75	0.87	0.91	0.92	0.93	0.94	0.95
0	—	0.75	0.87	0.91	0.92	0.93	0.94	0.95
0.27	—	0.75	0.87	0.91	0.92	0.93	0.94	0.95
0.53	0.14	0.77	0.87	0.91	0.94	0.93	0.94	0.95
0.80	0.26	0.79	0.87	0.91	0.93	0.93	0.94	0.95
1.07	0.40	0.80	0.88	0.90	0.93	0.93	0.94	0.96
1.33	0.78	0.84	0.88	0.92	0.94	0.93	0.94	0.96
2.00	0.94	0.94	0.93	0.94	0.95	0.94	0.95	0.96
2.67	1.00	0.97	0.96	0.96	0.96	0.96	0.96	0.96
3.33	1.00	1.00	0.99	0.98	0.98	0.98	0.97	0.97
4.00	1.00	1.00	1.00	0.99	0.99	0.99	0.98	0.98
4.67	1.00	1.00	1.00	1.00	1.00	1.00	0.98	0.99
5.67	1.00	1.00	1.00	1.00	1.00	1.00	0.99	0.99
7.67	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00

TABLE A-2. EXPERIMENTAL VELOCITY DISTRIBUTION IN WAKE OF MODEL B

	r/R	X/D							
		2	4	6	8	10	12	16	20
V/V_∞	4.70	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.99
	3.90	1.00	1.00	1.00	0.99	0.99	0.98	0.99	0.98
	3.10	1.00	1.00	1.00	0.99	0.98	0.98	0.98	0.98
	2.70	1.00	1.00	0.99	0.98	0.97	0.97	0.97	0.97
	2.30	1.00	0.98	0.97	0.96	0.96	0.96	0.96	0.97
	1.90	0.91	0.90	0.94	0.94	0.94	0.95	0.95	0.96
	1.50	0.55	0.84	0.89	0.92	0.92	0.94	0.95	0.95
	1.10	0	0.79	0.88	0.90	0.91	0.93	0.95	0.95
	0.90	0	0.75	0.86	0.90	0.91	0.93	0.94	0.95
	0.70	0	0.74	0.85	0.90	0.91	0.92	0.94	0.95
	0.50	0	0.78	0.85	0.89	0.91	0.92	0.94	0.95
	0.30	0	0.70	0.85	0.89	0.91	0.92	0.94	0.94
	0.10	0	0.69	0.84	0.89	0.91	0.92	0.94	0.95
	0.10	0	0.69	0.84	0.89	0.91	0.92	0.94	0.95
	0.30	0	0.70	0.85	0.89	0.91	0.92	0.94	0.94
	0.50	0	0.78	0.85	0.89	0.91	0.92	0.94	0.95
	0.70	0	0.74	0.85	0.90	0.91	0.92	0.94	0.95
	0.90	0	0.75	0.86	0.90	0.91	0.93	0.94	0.95
	1.10	0	0.79	0.88	0.90	0.91	0.93	0.95	0.95
	1.50	0.55	0.84	0.89	0.92	0.92	0.94	0.95	0.95
	1.90	0.91	0.90	0.94	0.94	0.94	0.95	0.95	0.96
	2.30	1.00	0.98	0.97	0.96	0.96	0.96	0.96	0.97
	2.70	1.00	1.00	0.99	0.98	0.97	0.97	0.97	0.97
	3.10	1.00	1.00	1.00	0.99	0.98	0.98	0.98	0.98
	3.90	1.00	1.00	1.00	0.99	0.99	0.98	0.99	0.98
	4.70	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.99

TABLE A-3. EXPERIMENTAL VELOCITY DISTRIBUTION IN WAKE OF MODEL C

	r/R	X/D 2	4	6	8	10	12	16	20
V/V_∞	7.67	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
	5.67	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
	4.67	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.99
	4.00	1.00	1.00	1.00	1.00	1.00	1.00	0.99	0.98
	3.33	1.00	1.00	1.00	1.00	0.99	0.98	0.95	0.97
	2.67	1.00	0.98	0.99	0.98	0.97	0.97	0.96	0.96
	2.00	1.00	0.95	0.95	0.95	0.95	0.95	0.95	0.96
	1.33	0.41	0.82	0.88	0.91	0.92	0.94	0.94	0.95
	1.07	0.14	0.77	0.87	0.90	0.92	0.93	0.94	0.95
	0.80		0.72	0.85	0.90	0.90	0.93	0.94	0.95
	0.53		0.69	0.85	0.90	0.90	0.93	0.94	0.95
	0.27		0.67	0.85	0.89	0.91	0.93	0.94	0.95
	0		0.66	0.85	0.89	0.91	0.92	0.93	0.94
	0.27		0.67	0.85	0.89	0.91	0.93	0.94	0.95
	0.53		0.69	0.85	0.90	0.90	0.93	0.94	0.95
	0.80		0.72	0.85	0.90	0.90	0.93	0.94	0.95
	1.07	0.14	0.77	0.87	0.90	0.92	0.93	0.94	0.95
	1.33	0.41	0.82	0.88	0.91	0.92	0.94	0.94	0.95
	2.00	1.00	0.95	0.95	0.95	0.95	0.95	0.95	0.96
	2.67	1.00	0.98	0.99	0.98	0.97	0.97	0.96	0.96
	3.33	1.00	1.00	1.00	1.00	0.99	0.98	0.95	0.97
	4.00	1.00	1.00	1.00	1.00	1.00	1.00	0.99	0.98
	4.67	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.99
	5.67	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
	7.67	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00

TABLE A-4. EXPERIMENTAL VELOCITY DISTRIBUTION IN WAKE OF MODEL D

	r/R	X/D 2	4	6	8	10	12	16	20
$\frac{V}{V_\infty}$	7.67	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
	5.67	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
	4.67	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
	4.00	1.00	0.99	1.00	1.00	1.00	1.00	0.99	0.99
	3.33	1.00	0.99	0.99	1.00	0.99	0.99	0.98	0.98
	2.67	1.00	0.99	0.99	0.99	0.98	0.98	0.98	0.98
	2.00	1.00	0.96	0.96	0.96	0.96	0.96	0.96	0.96
	1.33	0.66	0.85	0.90	0.92	0.93	0.94	0.95	0.96
	1.07	0.41	0.82	0.89	0.92	0.92	0.93	0.94	0.96
	0.80	0.17	0.79	0.88	0.90	0.92	0.93	0.94	0.96
	0.53	0.17	0.77	0.87	0.90	0.92	0.93	0.94	0.96
	0.27	0.14	0.75	0.86	0.90	0.92	0.93	0.93	0.96
	0	0.14	0.75	0.86	0.90	0.92	0.93	0.93	0.96
	0.27	0.14	0.75	0.86	0.90	0.92	0.93	0.93	0.96
	0.53	0.17	0.77	0.87	0.90	0.92	0.93	0.94	0.96
	0.80	0.17	0.79	0.88	0.90	0.92	0.93	0.94	0.96
	1.07	0.41	0.82	0.89	0.92	0.92	0.93	0.94	0.96
	1.33	0.66	0.85	0.90	0.92	0.93	0.94	0.95	0.96
	2.00	1.00	0.96	0.96	0.96	0.96	0.96	0.96	0.96
	2.67	1.00	0.99	0.99	0.98	0.98	0.98	0.98	0.98
	3.33	1.00	0.99	0.99	1.00	0.99	0.99	0.98	0.98
	4.00	1.00	0.99	1.00	1.00	1.00	1.00	0.99	0.99
	4.67	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
	5.67	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
	7.67	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00

TABLE A-5. EXPERIMENTAL VELOCITY DISTRIBUTION IN WAKE OF MODEL E

r/R	X/D = 2	4	6	8	10	12	16	20
	V/V_∞							
7.67	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
5.67	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
4.67	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.99
4.00	1.00	1.00	1.00	1.00	0.99	0.99	0.99	0.98
3.33	1.00	1.00	1.00	1.00	0.99	0.99	0.99	0.98
2.67	0.94	0.99	0.99	0.98	0.98	0.98	0.97	0.97
2.00	0.94	0.97	0.97	0.96	0.96	0.96	0.95	0.96
1.33	0.68	0.87	0.90	0.92	0.93	0.94	0.95	0.95
1.07	0.40	0.82	0.88	0.90	0.92	0.94	0.94	0.95
0.80	0.17	0.77	0.87	0.90	0.92	0.94	0.95	0.95
0.53	0.00	0.73	0.87	0.90	0.92	0.94	0.95	0.95
0.27	0.00	0.71	0.86	0.90	0.92	0.94	0.95	0.95
0	0.00	0.71	0.86	0.90	0.91	0.93	0.94	0.95
0.27	0.00	0.71	0.86	0.90	0.92	0.94	0.95	0.95
0.53	0.00	0.73	0.87	0.90	0.92	0.94	0.95	0.95
0.80	0.17	0.77	0.87	0.90	0.92	0.94	0.95	0.95
1.07	0.40	0.82	0.88	0.90	0.92	0.94	0.94	0.95
1.33	0.68	0.87	0.90	0.92	0.93	0.94	0.95	0.95
2.00	0.94	0.97	0.97	0.96	0.96	0.96	0.96	0.96
2.67	0.94	0.99	0.99	0.98	0.98	0.98	0.97	0.97
3.33	1.00	1.00	1.00	1.00	0.99	0.99	0.98	0.98
4.00	1.00	1.00	1.00	1.00	0.99	0.99	0.99	0.98
4.67	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.99
5.67	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
7.67	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00

TABLE A-6. EXPERIMENTAL VELOCITY DISTRIBUTION IN WAKE OF MODEL F

	r/R	X/D							
		2	4	6	8	10	12	16	20
V/V_∞	7.67	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
	5.67	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
	4.67	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
	4.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
	3.33	1.00	1.00	1.00	1.00	0.99	1.00	0.99	0.99
	2.67	1.00	1.00	1.00	1.00	0.99	0.99	0.98	0.98
	2.00	1.00	0.99	0.98	0.97	0.97	0.97	0.97	0.97
	1.33	0.92	0.93	0.94	0.94	0.94	0.95	0.96	0.96
	1.07	0.73	0.87	0.91	0.93	0.94	0.94	0.96	0.96
	0.80	0.47	0.84	0.90	0.92	0.93	0.94	0.96	0.96
	0.53	0.20	0.81	0.90	0.92	0.93	0.94	0.96	0.96
	0.27	0.00	0.80	0.88	0.92	0.93	0.94	0.95	0.96
	0	0.00	0.80	0.88	0.91	0.93	0.94	0.95	0.96
	0.27	0.00	0.80	0.88	0.92	0.93	0.94	0.95	0.96
	0.53	0.20	0.81	0.90	0.92	0.93	0.94	0.96	0.96
	0.80	0.47	0.84	0.90	0.92	0.93	0.94	0.96	0.96
	1.07	0.73	0.87	0.91	0.93	0.94	0.94	0.96	0.96
	1.33	0.92	0.91	0.94	0.94	0.94	0.94	0.96	0.96
	2.00	1.00	0.99	0.98	0.97	0.97	0.97	0.97	0.97
	2.67	1.00	1.00	1.00	1.00	0.99	0.99	0.98	0.98
	3.33	1.00	1.00	1.00	1.00	0.99	1.00	0.99	0.99
	4.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
	4.67	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
	5.67	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
	7.67	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00

TABLE A-7. EXPERIMENTAL VELOCITY DISTRIBUTION IN WAKE OF MODEL G

r/R	X/D 2	4	6	8	10	12	16	20
7.67	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
5.67	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
4.67	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
4.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
3.33	1.00	1.00	1.00	1.00	0.99	1.00	1.00	1.00
2.67	1.00	1.00	1.00	1.00	0.98	1.00	0.99	0.99
2.00	1.00	1.00	0.98	0.99	0.95	0.98	0.98	0.98
1.33	0.93	0.95	0.95	0.95	0.94	0.95	0.96	0.97
1.07	0.82	0.90	0.93	0.94	0.94	0.95	0.96	0.96
0.80	0.68	0.88	0.90	0.93	0.93	0.95	0.95	0.96
0.53	0.50	0.82	0.88	0.92	0.93	0.95	0.95	0.96
0.27	0.33	0.81	0.88	0.90	0.92	0.94	0.95	0.95
0	0.29	0.80	0.87	0.90	0.93	0.93	0.94	0.95
0.27	0.33	0.81	0.88	0.90	0.93	0.94	0.95	0.95
0.53	0.50	0.82	0.88	0.92	0.94	0.95	0.95	0.96
0.80	0.68	0.88	0.90	0.93	0.94	0.95	0.95	0.96
1.07	0.82	0.90	0.93	0.94	0.95	0.95	0.96	0.96
1.33	0.93	0.95	0.95	0.95	0.98	0.95	0.96	0.97
2.00	1.00	1.00	0.98	0.99	0.99	0.98	0.98	0.98
2.67	1.00	1.00	1.00	1.00	1.00	1.00	0.99	0.99
3.33	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
4.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
4.67	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
5.67	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
7.67	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00

V/V_∞

TABLE A-8. EXPERIMENTAL VELOCITY DISTRIBUTION IN WAKE OF MODEL H

	r/R	X/D							
		2	4	6	8	10	12	16	20
$\frac{V}{V_\infty}$	7.67	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
	5.67	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
	4.67	1.00	1.00	1.00	1.00	1.00	1.00	0.99	0.99
	4.00	0.99	1.00	0.99	0.99	0.99	0.99	0.99	0.98
	3.33	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.98
	2.67	0.99	0.99	0.99	0.99	0.99	0.98	0.98	0.98
	2.00	0.99	0.99	0.99	0.99	0.98	0.98	0.98	0.97
	1.33	0.98	0.98	0.98	0.97	0.97	0.97	0.98	0.97
	1.07	0.97	0.97	0.97	0.96	0.96	0.96	0.97	0.96
	0.80	0.96	0.95	0.95	0.95	0.95	0.96	0.96	0.96
	0.53	0.89	0.92	0.93	0.95	0.94	0.94	0.95	0.95
	0.27	0.79	0.90	0.91	0.92	0.93	0.94	0.95	0.95
	0	0.74	0.88	0.90	0.93	0.93	0.94	0.95	0.95
	0.27	0.79	0.90	0.91	0.92	0.93	0.94	0.95	0.95
	0.53	0.89	0.92	0.93	0.95	0.94	0.94	0.95	0.95
	0.80	0.96	0.95	0.95	0.95	0.95	0.96	0.96	0.96
	1.07	0.97	0.97	0.97	0.96	0.96	0.96	0.97	0.96
	1.33	0.91	0.98	0.98	0.97	0.97	0.97	0.98	0.97
	2.00	0.99	0.99	0.99	0.99	0.98	0.98	0.98	0.97
	2.67	0.99	0.99	0.99	0.99	0.99	0.98	0.98	0.98
	3.33	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.98
	4.00	0.99	1.00	0.99	0.99	0.99	0.99	0.99	0.98
	4.67	1.00	1.00	1.00	1.00	1.00	1.00	0.99	0.99
	5.67	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
	7.67	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00

TABLE A-9. EXPERIMENTAL VELOCITY DISTRIBUTION IN WAKE OF MODEL I

	r/R	X/D							
		2	4	6	8	10	12	16	20
$\frac{V}{V_\infty}$	7.67	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
	5.67	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
	4.67	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
	4.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
	3.33	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
	2.67	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
	2.00	1.00	1.00	1.00	1.00	0.99	0.99	0.99	0.99
	1.33	0.99	0.99	0.97	0.96	0.97	0.96	0.96	0.96
	1.07	0.98	0.97	0.95	0.95	0.95	0.96	0.95	0.96
	0.80	0.93	0.93	0.93	0.94	0.94	0.94	0.95	0.96
	0.53	0.84	0.88	0.90	0.92	0.93	0.93	0.94	0.96
	0.27	0.75	0.84	0.88	0.92	0.92	0.92	0.93	0.95
	0	0.74	0.81	0.86	0.90	0.90	0.92	0.93	0.95
	0.27	0.75	0.84	0.88	0.92	0.92	0.92	0.93	0.95
	0.53	0.84	0.88	0.90	0.92	0.93	0.93	0.94	0.96
	0.80	0.93	0.93	0.93	0.94	0.94	0.94	0.95	0.96
	1.07	0.98	0.97	0.95	0.95	0.95	0.96	0.95	0.96
	1.33	0.99	0.99	0.97	0.96	0.97	0.96	0.96	0.96
	2.00	1.00	1.00	1.00	1.00	0.99	0.99	0.99	0.99
	2.67	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
	3.33	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
	4.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
	4.67	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
	5.67	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
	7.67	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00

TABLE A-10. EXPERIMENTAL VELOCITY DISTRIBUTION IN WAKE OF MODEL J

Values are V/V_∞.

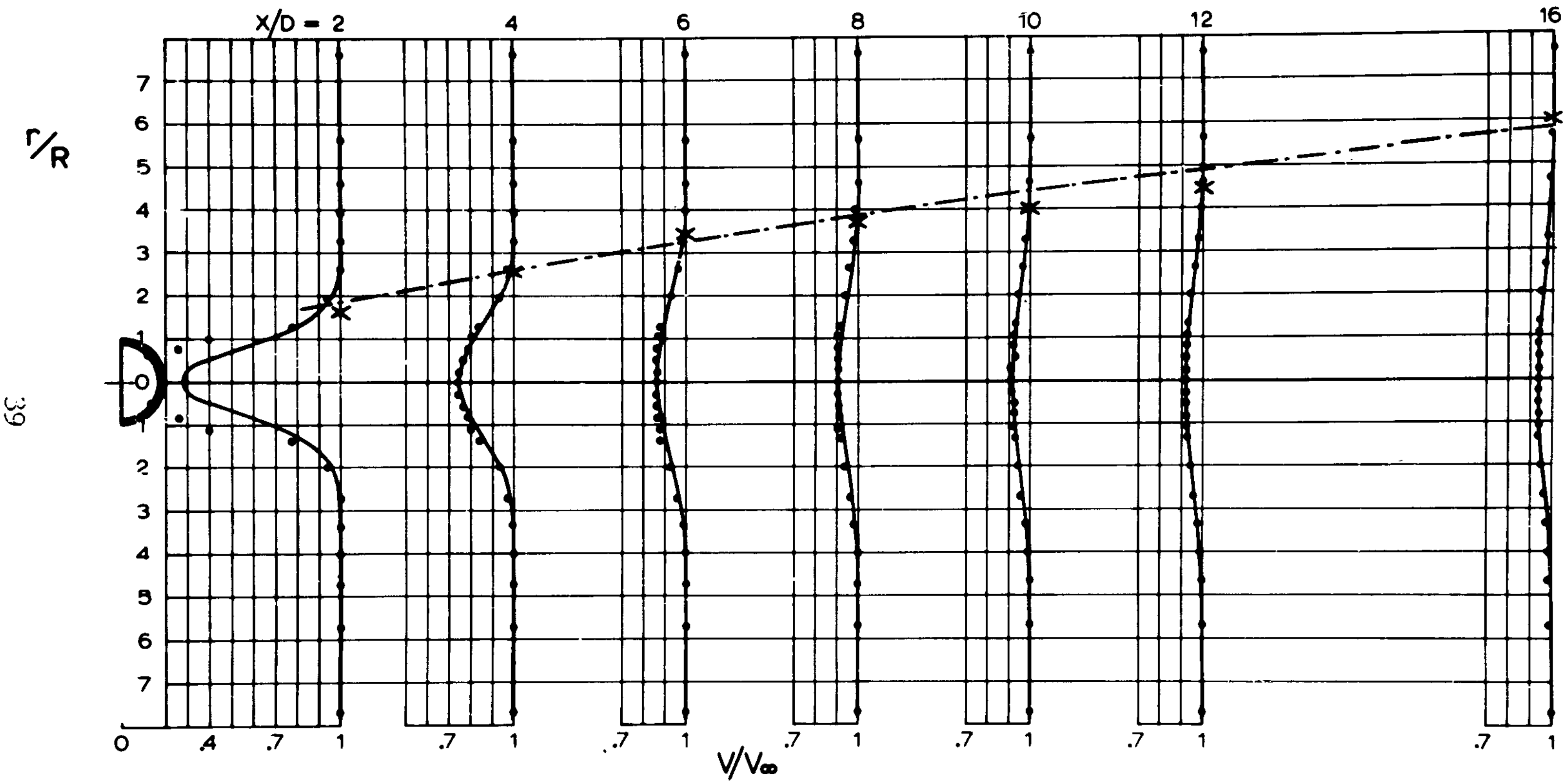
r/R	X/D = 2	4	6	8	10	12	16	20
7.67	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
5.67	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
4.67	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
4.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
3.33	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
2.67	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.99
2.00	1.00	1.00	1.00	1.00	1.00	1.00	0.99	0.98
1.33	0.99	1.00	0.97	0.97	0.97	0.97	0.96	0.96
1.07	0.99	0.99	0.94	0.95	0.95	0.95	0.95	0.95
0.80	0.98	0.95	0.90	0.93	0.93	0.93	0.95	0.96
0.53	0.84	0.86	0.90	0.90	0.91	0.91	0.94	0.95
0.27	0.71	0.79	0.89	0.86	0.90	0.90	0.93	0.95
0	0.66	0.75	0.88	0.85	0.89	0.90	0.92	0.94
0.27	0.71	0.79	0.89	0.86	0.90	0.90	0.93	0.95
0.53	0.84	0.86	0.90	0.90	0.91	0.91	0.94	0.95
0.80	0.98	0.95	0.90	0.93	0.93	0.93	0.95	0.96
1.07	0.99	0.99	0.94	0.95	0.95	0.95	0.95	0.95
1.33	0.99	1.00	0.97	0.97	0.97	0.97	0.96	0.96
2.00	1.00	1.00	1.00	1.00	1.00	1.00	0.99	0.98
2.67	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.99
3.33	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
4.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
4.67	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
5.67	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
7.67	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00

TABLE A-11. EXPERIMENTAL VELOCITY DISTRIBUTION IN WAKE OF MODEL K

	r/R	X/D							
		2	4	6	8	10	12	16	18
V/V_∞	7.67	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
	5.67	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
	4.67	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
	4.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
	3.33	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
	2.67	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
	2.00	0.99	1.00	1.00	1.00	0.99	1.00	0.99	0.99
	1.33	0.99	0.99	0.99	0.98	0.98	0.97	0.96	0.97
	1.07	0.99	0.99	0.97	0.95	0.96	0.95	0.95	0.95
	0.80	0.98	0.96	0.93	0.92	0.93	0.93	0.94	0.94
	0.53	0.87	0.85	0.88	0.91	0.90	0.92	0.93	0.94
	0.27	0.72	0.76	0.83	0.86	0.86	0.90	0.93	0.93
	0	0.64	0.71	0.83	0.86	0.85	0.88	0.92	0.92
	0.27	0.72	0.76	0.83	0.86	0.86	0.90	0.93	0.93
	0.53	0.87	0.85	0.88	0.91	0.90	0.92	0.93	0.94
	0.80	0.98	0.96	0.93	0.92	0.93	0.93	0.94	0.94
	1.07	0.99	0.99	0.97	0.95	0.96	0.95	0.95	0.95
	1.33	0.99	0.99	0.99	0.98	0.98	0.97	0.96	0.97
	2.00	0.99	1.00	1.00	1.00	0.99	1.00	0.99	0.99
	2.67	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
	3.33	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
	4.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
	4.67	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
	5.67	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
	7.67	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00

TABLE A-12. EXPERIMENTAL VELOCITY DISTRIBUTION IN WAKE OF MODEL L

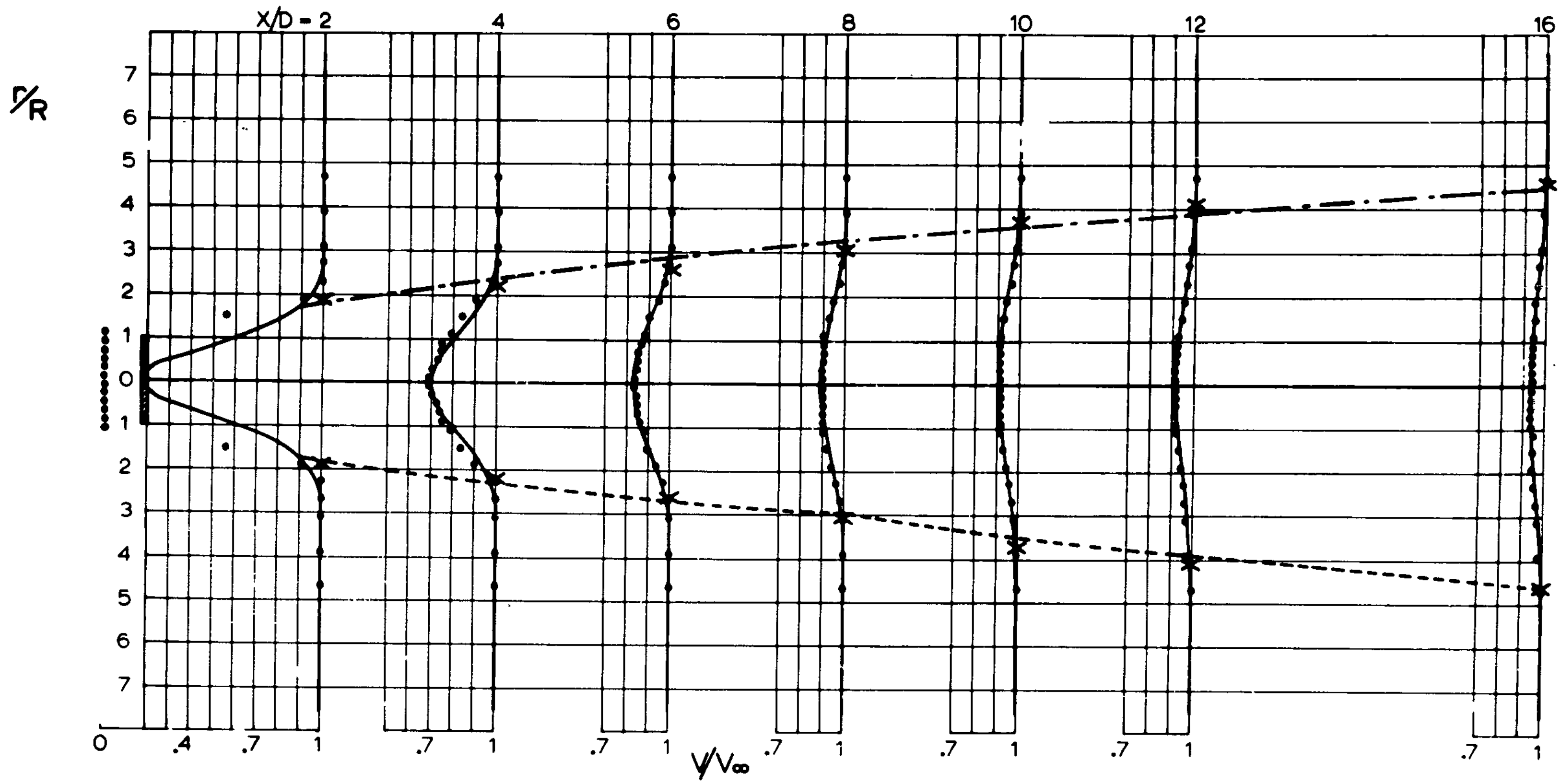
	r/R	x/D							
		2	4	6	8	10	12	16	20
	7.67	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
	5.67	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
	4.67	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
	4.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
	3.33	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
	2.67	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
	2.00	1.00	1.00	1.00	1.00	1.00	0.99	0.99	0.99
	1.33	0.99	0.99	0.98	0.97	0.98	0.98	0.95	0.96
	1.07	0.99	0.99	0.95	0.94	0.96	0.95	0.94	0.95
V/V_∞	0.80	0.97	0.96	0.90	0.91	0.93	0.93	0.94	0.95
	0.53	0.88	0.90	0.90	0.89	0.90	0.91	0.94	0.94
	0.27	0.72	0.77	0.87	0.88	0.86	0.90	0.93	0.93
	0	0.66	0.71	0.88	0.89	0.83	0.90	0.93	0.93
	0.27	0.72	0.77	0.87	0.88	0.86	0.90	0.93	0.93
	0.53	0.88	0.90	0.90	0.89	0.90	0.91	0.94	0.94
	0.80	0.97	0.96	0.90	0.91	0.93	0.93	0.94	0.95
	1.07	0.99	0.99	0.95	0.94	0.96	0.95	0.94	0.95
	1.33	0.99	0.99	0.98	0.97	0.98	0.98	0.95	0.96
	2.00	1.00	1.00	1.00	1.00	1.00	0.99	0.99	0.99
	2.67	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
	3.33	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
	4.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
	4.67	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
	5.67	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
	7.67	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00



FIGA-1 EXPERIMENTAL AND THEORETICAL VELOCITY DISTRIBUTION IN WAKE OF HOLLOW HEMISPHERE (CUP FORWARD) —— MODEL A

• EXPERIMENTAL POINTS
—— THEORETICAL CURVE

WAKE WIDTH : EXPERIMENTAL ×
EMPIRICAL, ONE LINE APPROXIMATION —·—



FIGA-2.EXPERIMENTAL AND THEORETICAL VELOCITY DISTRIBUTION IN WAKE OF DISK —— MODEL B

• EXPERIMENTAL POINTS
— THEORETICAL CURVE

WAKE WIDTH: EXPERIMENTAL ×
EMPIRICAL, ONE LINE APPROXIMATION —·—
EMPIRICAL, TWO LINE APPROXIMATION ---

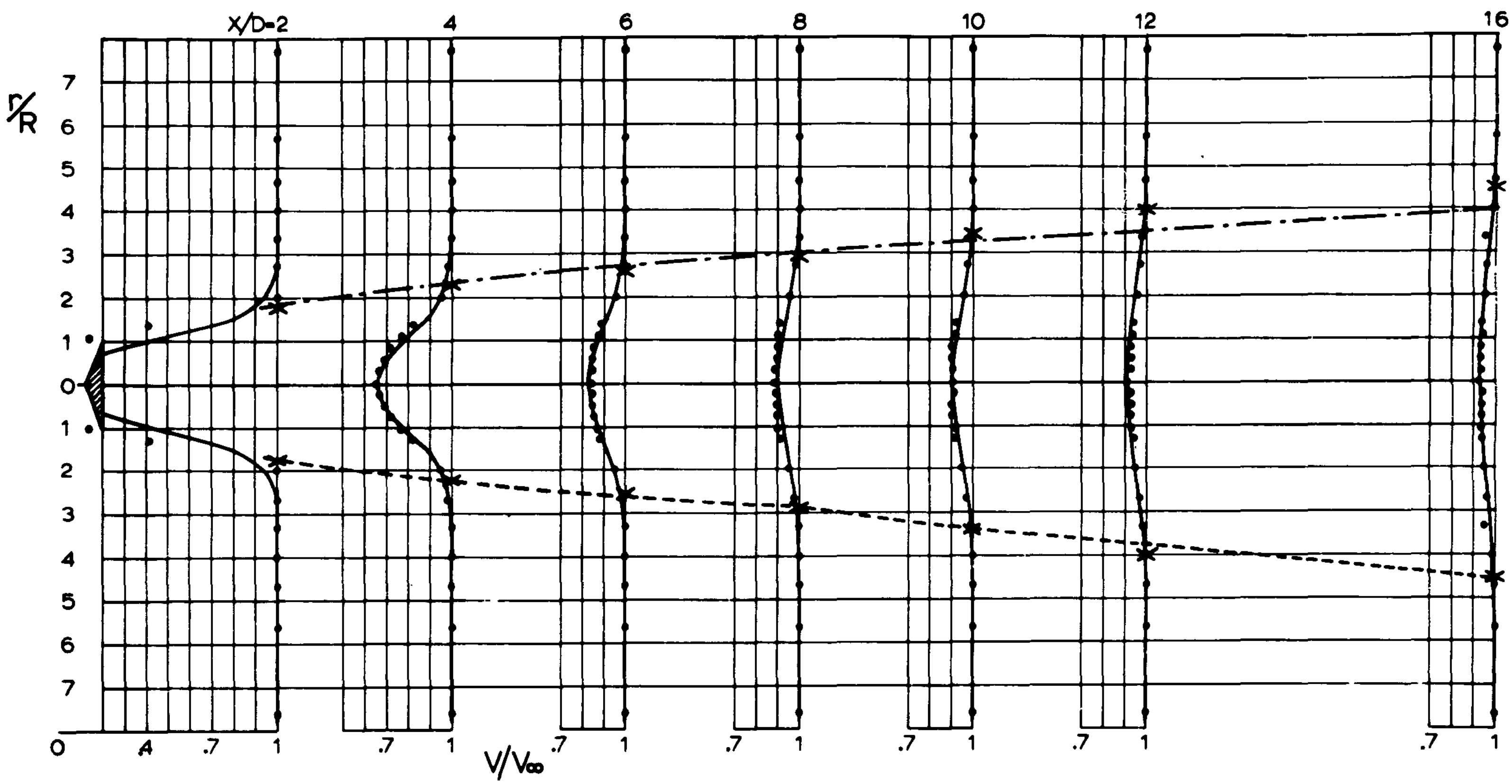
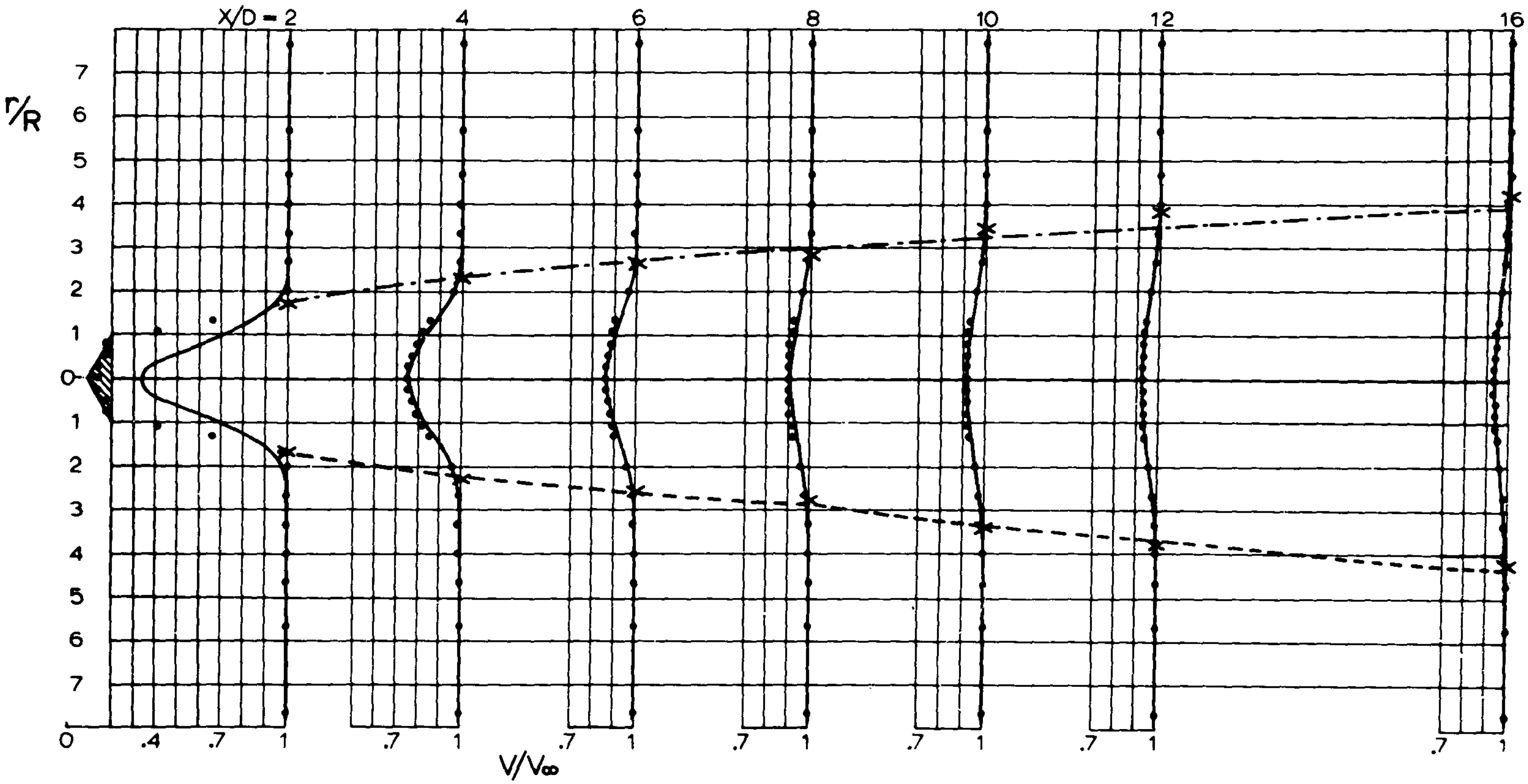


FIG A-3. EXPERIMENTAL AND THEORETICAL VELOCITY DISTRIBUTION IN WAKE OF CONE (α=75°) — MODEL C

• EXPERIMENTAL POINTS
— THEORETICAL CURVE

WAKE WIDTH: EXPERIMENTAL ×
EMPIRICAL, ONE LINE APPROXIMATION —·—
EMPIRICAL, TWO LINE APPROXIMATION - - -



FIGA-4. EXPERIMENTAL AND THEORETICAL VELOCITY DISTRIBUTION IN WAKE OF CONE ($\alpha = 55°$) — MODEL D

• EXPERIMENTAL POINTS
— THEORETICAL CURVE

WAKE WIDTH : EXPERIMENTAL ×
EMPIRICAL, ONE LINE APPROXIMATION —·—
EMPIRICAL, TWO LINE APPROXIMATION - - -

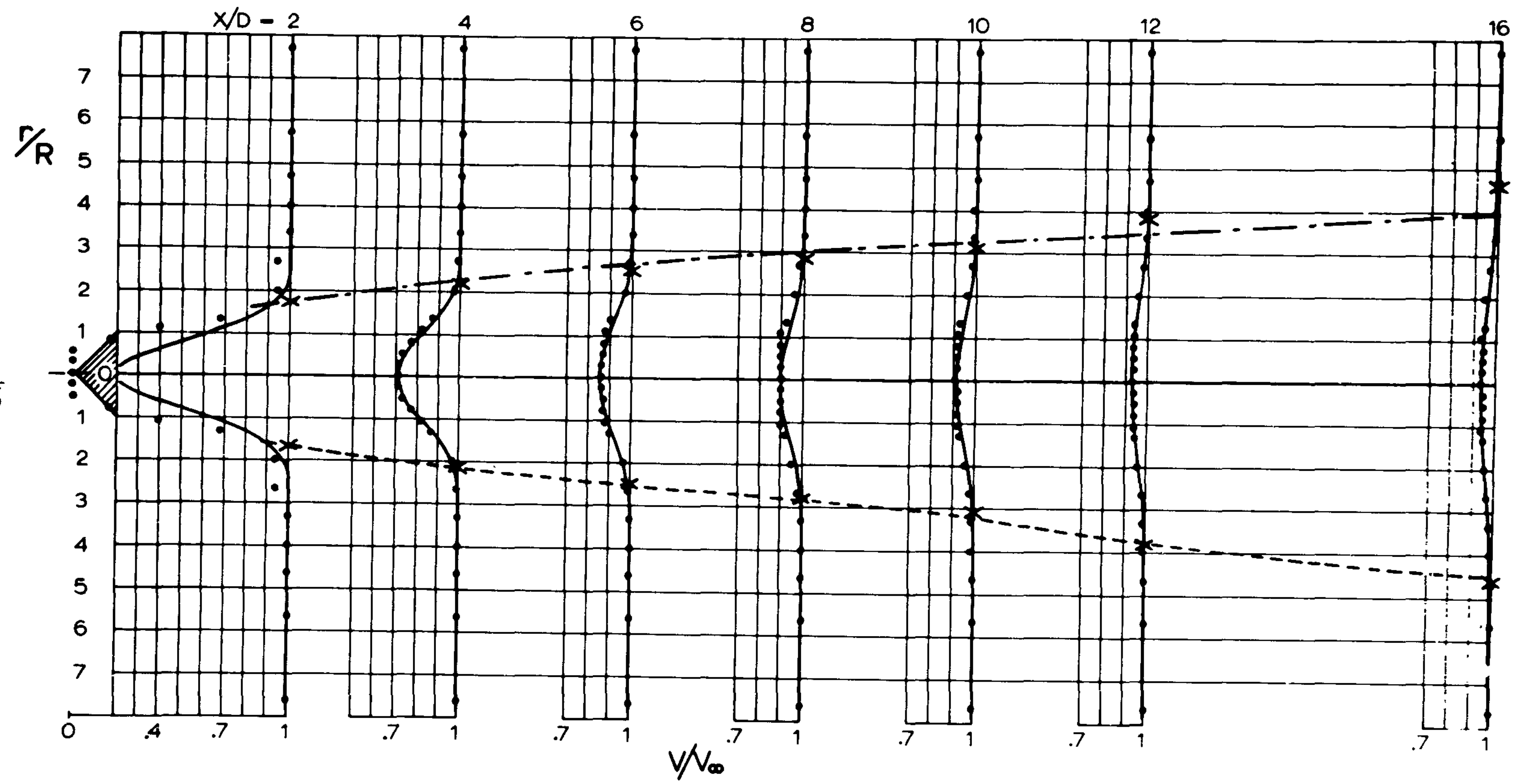


FIG A-5 EXPERIMENTAL AND THEORETICAL VELOCITY DISTRIBUTION IN WAKE OF CONE (α = 42.5°) — MODEL E

• EXPERIMENTAL POINTS
— THEORETICAL CURVE

WAKE WIDTH : EXPERIMENTAL ×
EMPIRICAL, ONE LINE APPROXIMATION —·—
EMPIRICAL, TWO LINE APPROXIMATION – – –

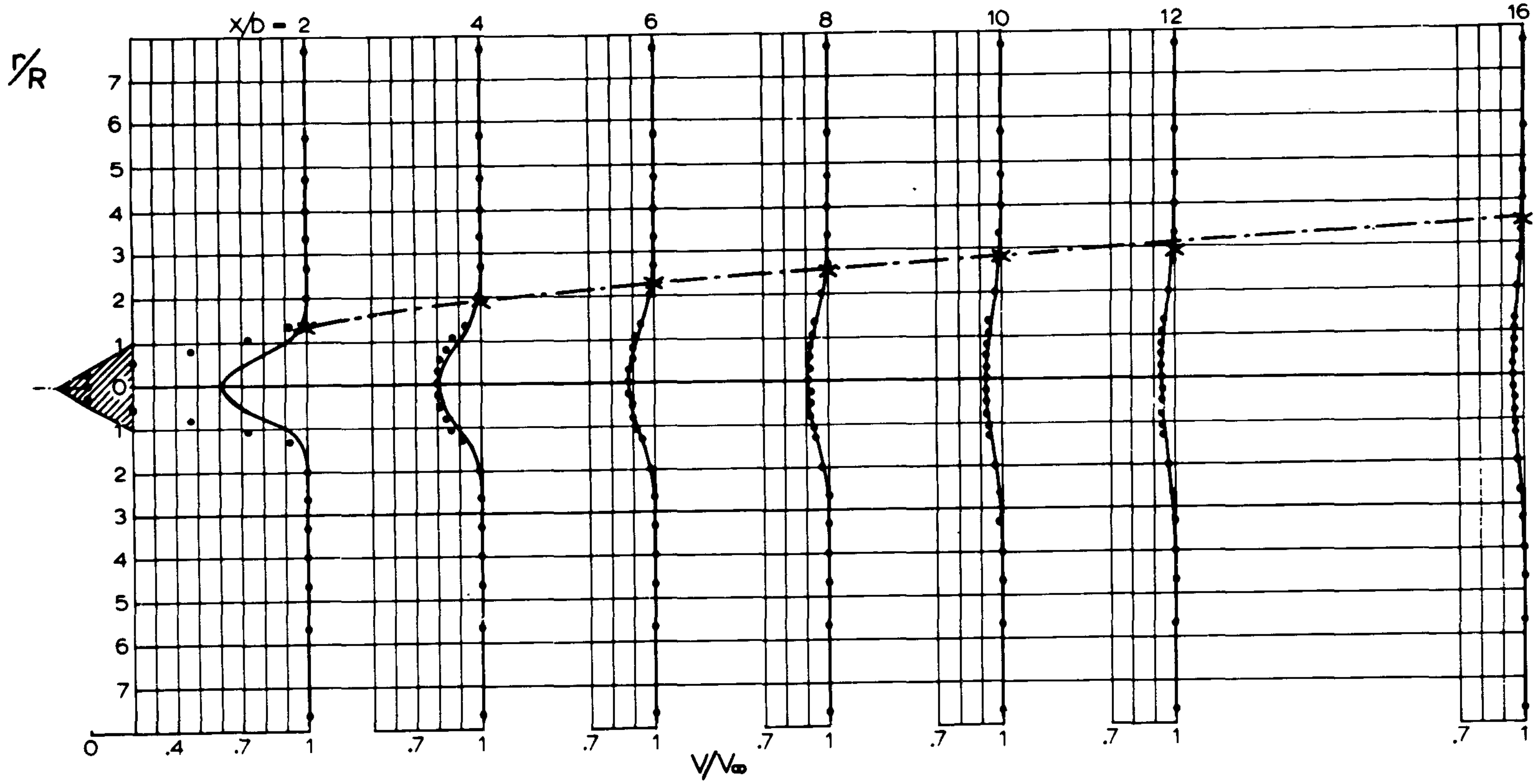


FIG A-6 EXPERIMENTAL AND THEORETICAL VELOCITY DISTRIBUTION IN WAKE OF CONE ($\alpha = 30°$) — MODEL F

• EXPERIMENTAL POINTS
— THEORETICAL CURVE

WAKE WIDTH: EXPERIMENTAL ×
EMPIRICAL, ONE LINE APPROXIMATION —·—

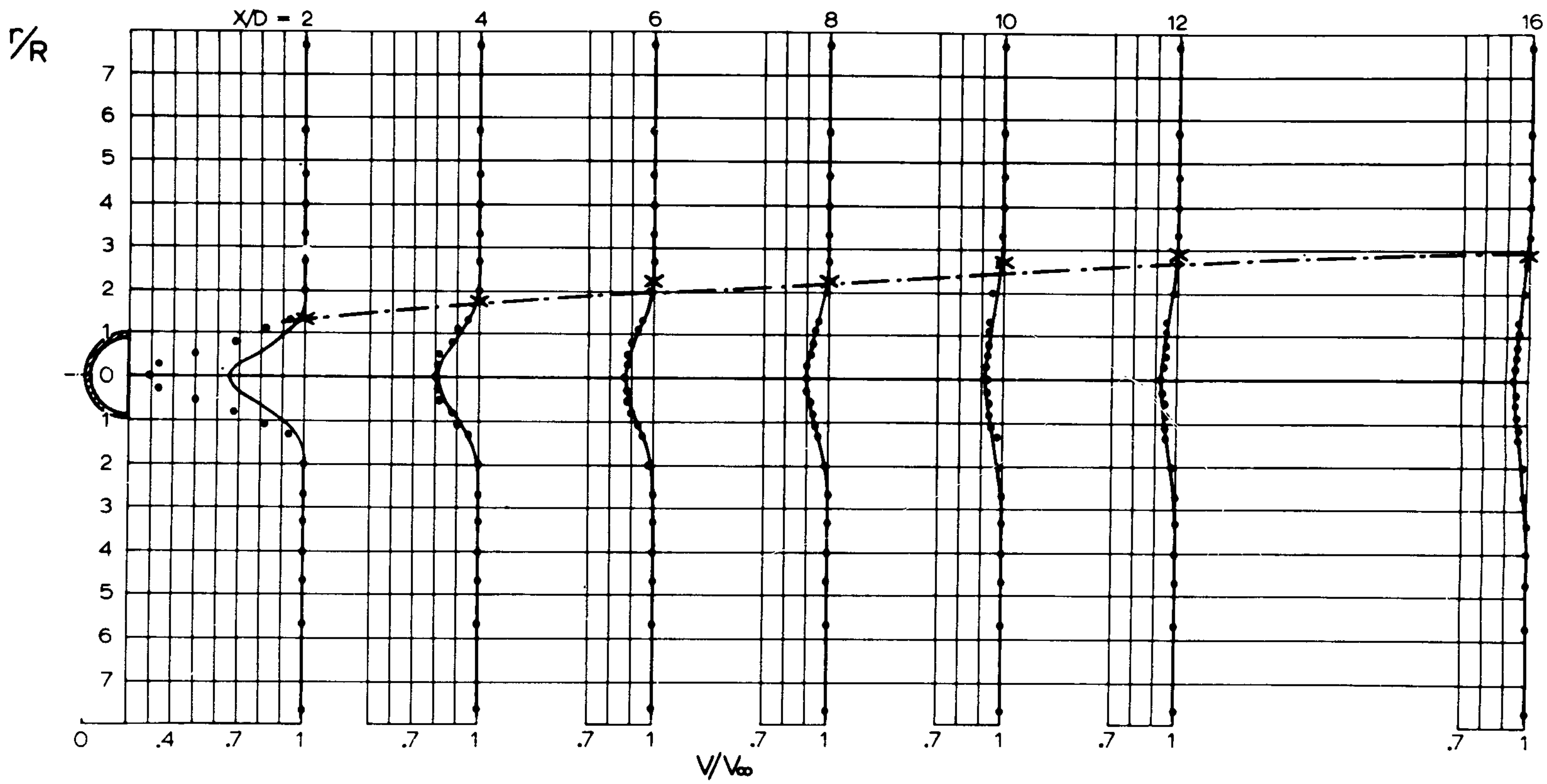


FIG A-7 EXPERIMENTAL AND THEORETICAL VELOCITY DISTRIBUTION IN WAKE OF HOLLOW HEMISPHERE (CUP BACKWARD) —— MODEL G

• EXPERIMENTAL POINTS
—— THEORETICAL CURVE

WAKE WIDTH: EXPERIMENTAL ×
EMPIRICAL, ONE LINE APPROXIMATION —·—

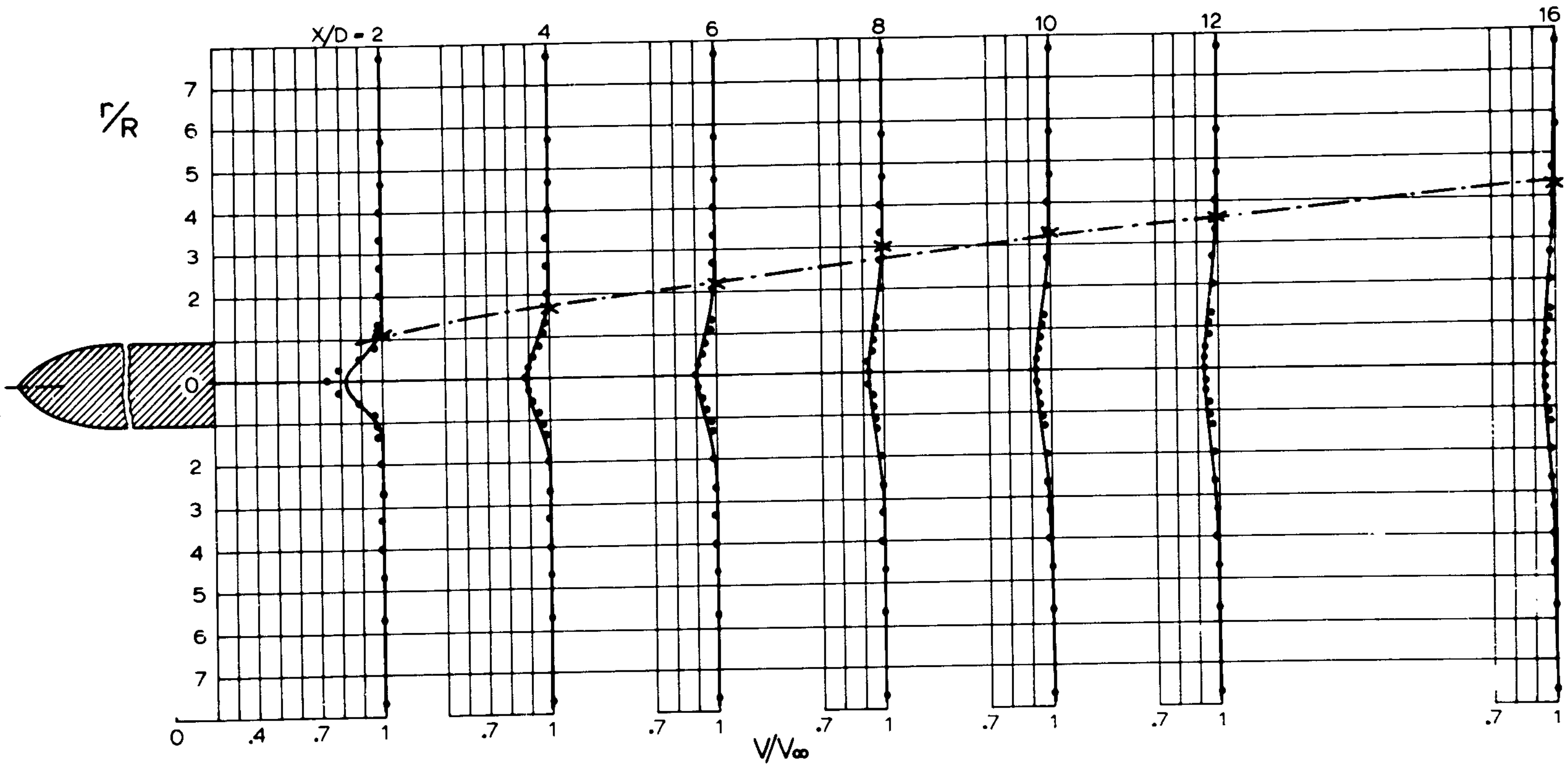


FIG A-8 EXPERIMENTAL AND THEORETICAL VELOCITY DISTRIBUTION IN WAKE OF OGIVE CYLINDER — MODEL H

• EXPERIMENTAL POINTS
— THEORETICAL CURVE

EXPERIMENTAL ×
WAKE WIDTH: EMPIRICAL, ONE LINE APPROXIMATION —·—

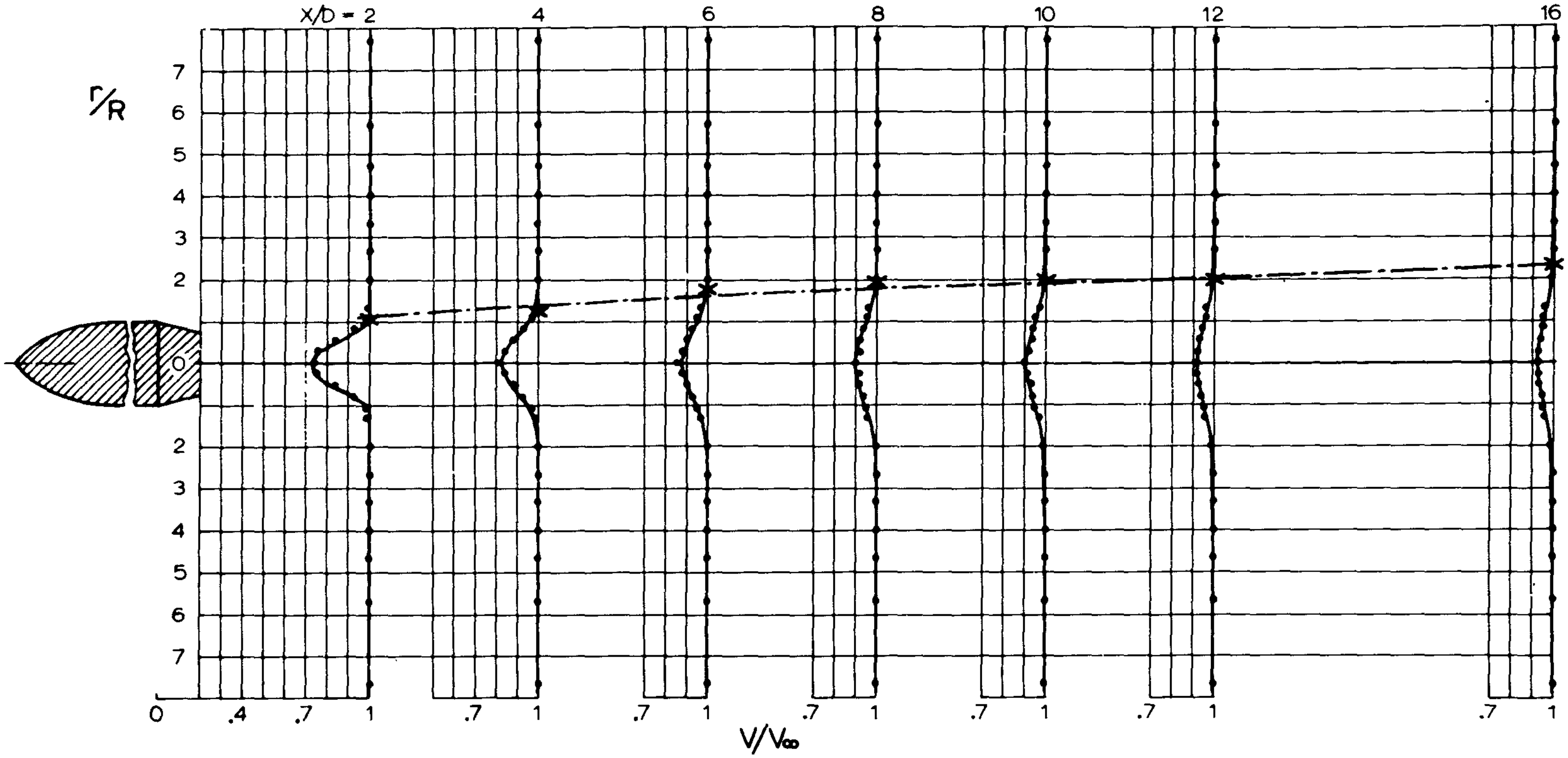


FIG A-9. EXPERIMENTAL AND THEORETICAL VELOCITY DISTRIBUTION IN WAKE OF OGIVE CYLINDER WITH AFTERBODY NO 1 — MODEL I

• EXPERIMENTAL POINTS
—— THEORETICAL CURVE

WAKE WIDTH : EXPERIMENTAL ×
EMPIRICAL, ONE LINE APPROXIMATION —·—

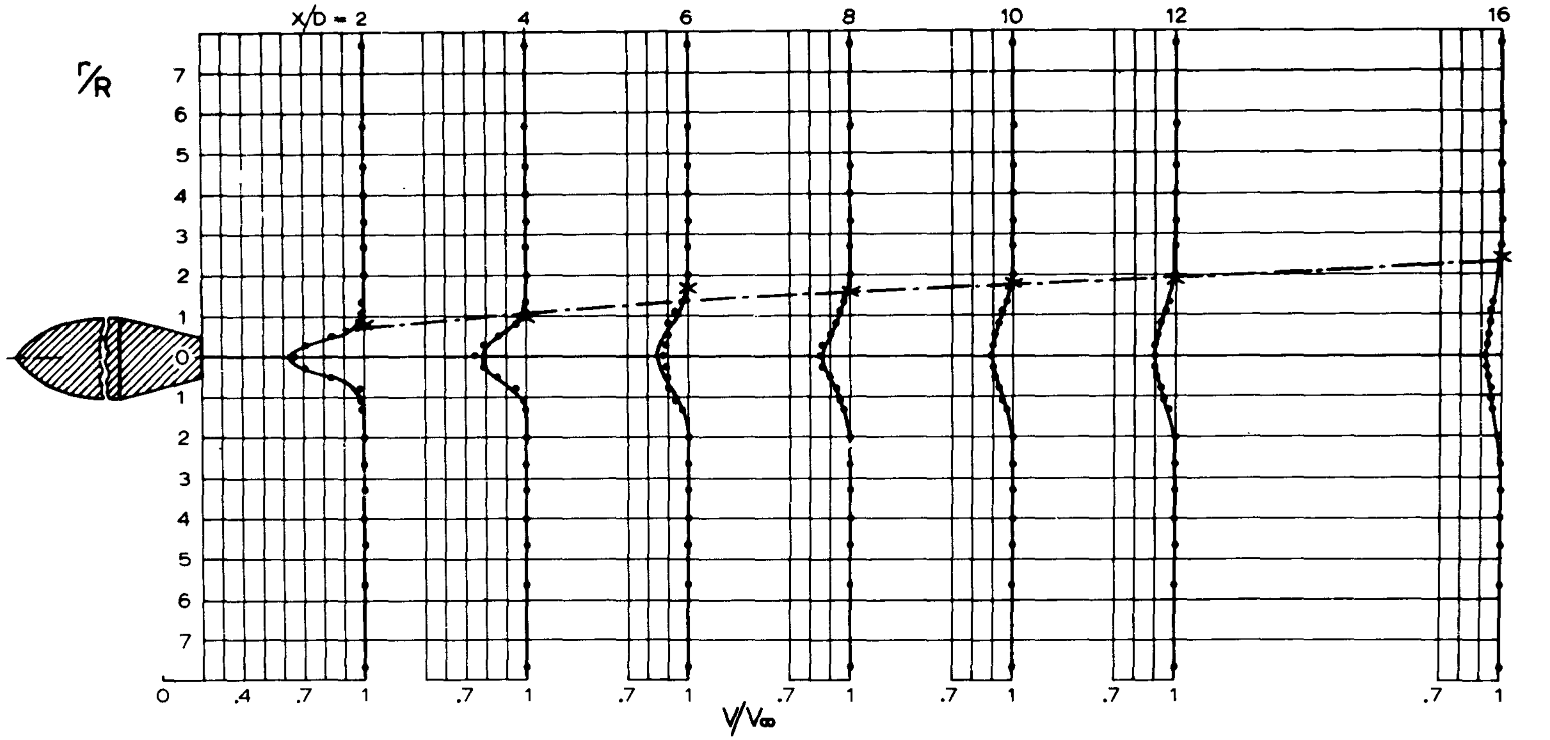


FIG A-10. EXPERIMENTAL AND THEORETICAL VELOCITY DISTRIBUTION IN WAKE OF OGIVE CYLINDER WITH AFTERBODY NO 2—MODEL J

• EXPERIMENTAL POINTS
— THEORETICAL CURVE

WAKE WIDTH: EXPERIMENTAL ×
EMPIRICAL, ONE LINE APPROXIMATION —·—

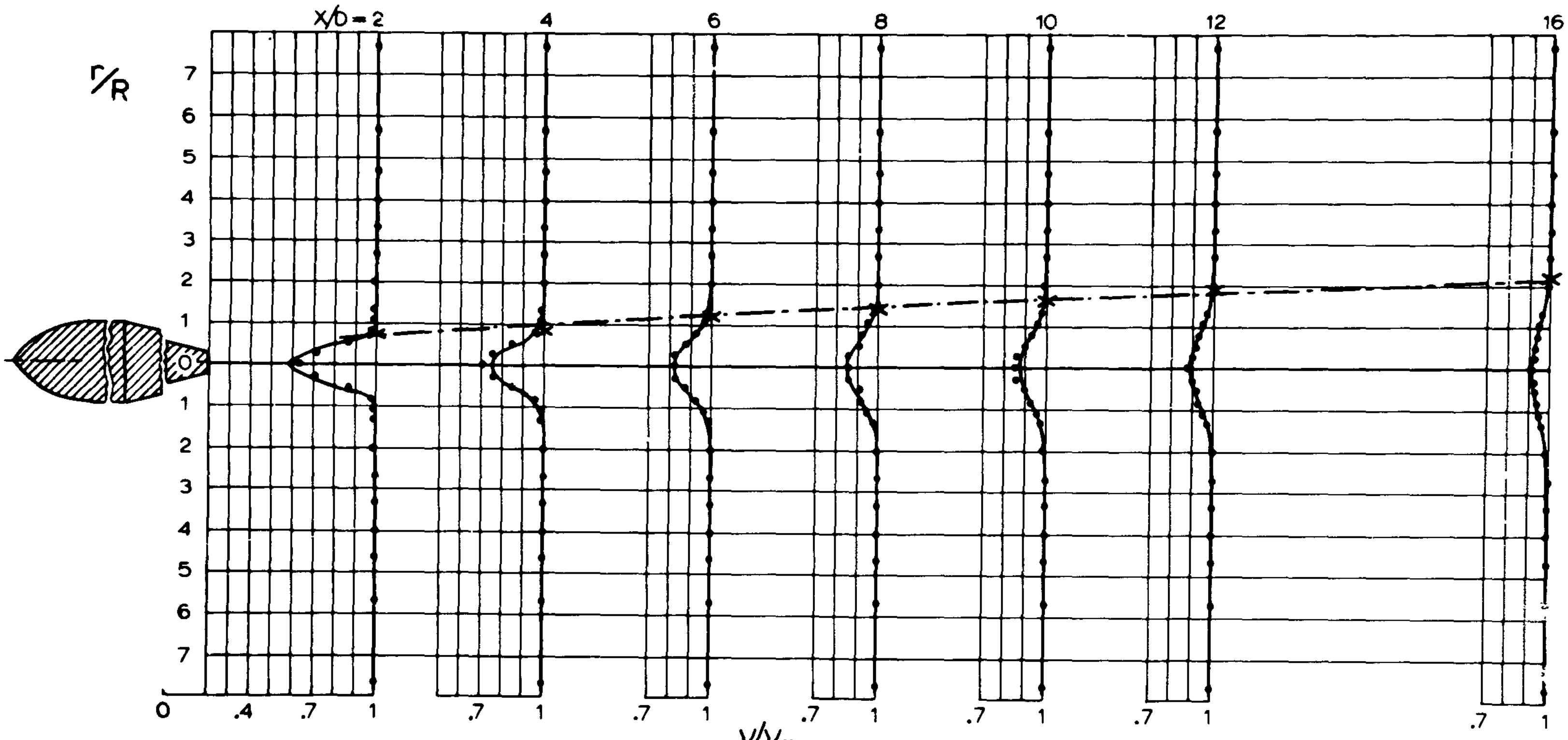


FIG A-11. EXPERIMENTAL AND THEORETICAL VELOCITY DISTRIBUTION IN WAKE OF OGIVE CYLINDER WITH AFTERBODY NO 3 — MODEL K

• EXPERIMENTAL POINTS
— THEORETICAL CURVE

WAKE WIDTH : EXPERIMENTAL ×
EMPIRICAL, ONE LINE APPROXIMATION —·—

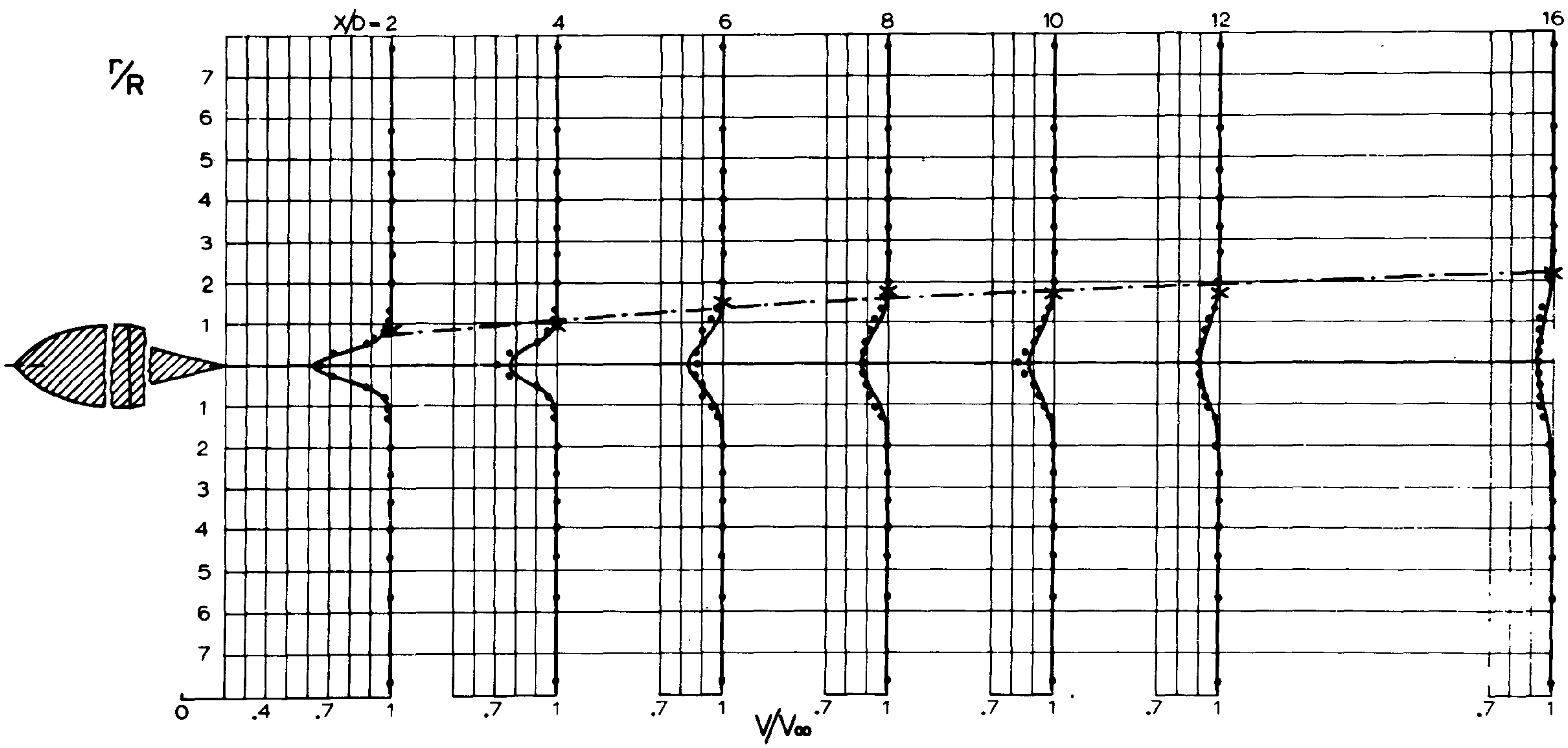


FIG A-12. EXPERIMENTAL AND THEORETICAL VELOCITY DISTRIBUTION IN WAKE OF OGIVE CYLINDER WITH AFTERBODY NO 4 — MODEL L

• EXPERIMENTAL POINTS
— THEORETICAL CURVE

WAKE WIDTH: EXPERIMENTAL ×
EMPIRICAL, ONE LINE APPROXIMATION —·—

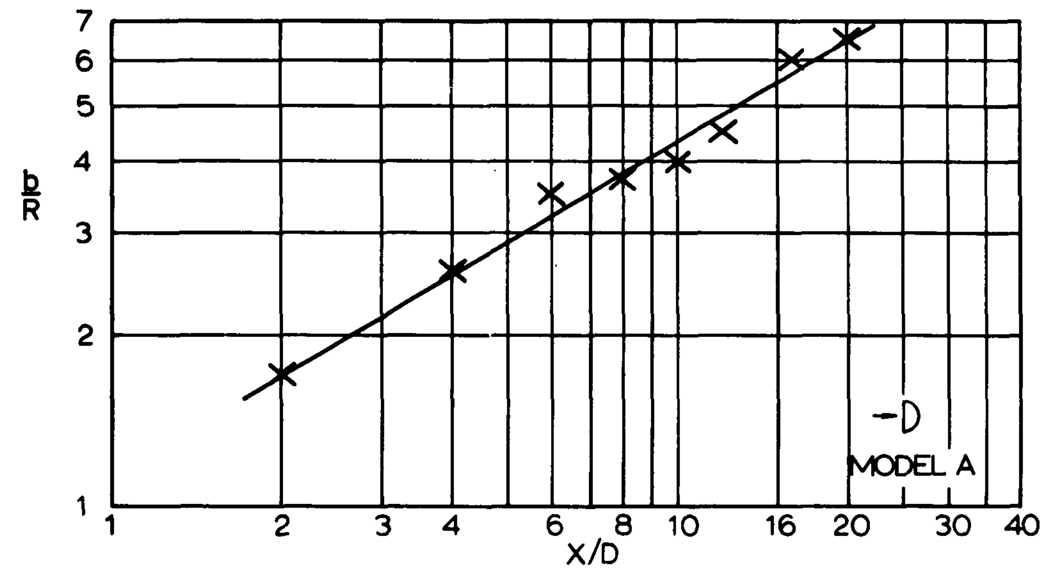


FIG A-13. EXPERIMENTAL WAKE WIDTH OF MODEL A

ONE LINE APPROXIMATION——

TWO LINE APPROXIMATION—-—

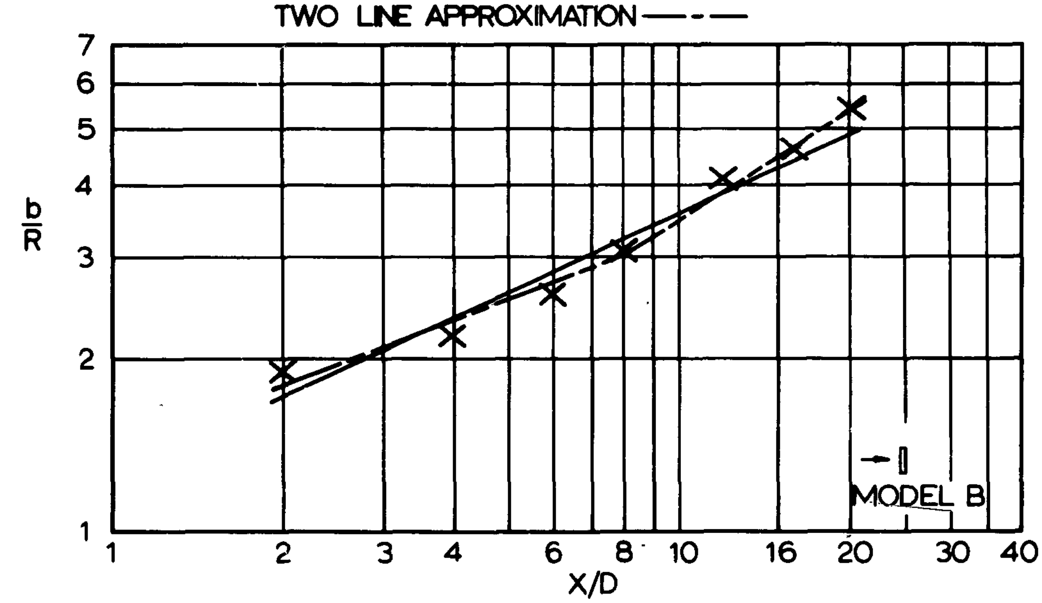


FIG A-14. EXPERIMENTAL WAKE WIDTH OF MODEL B

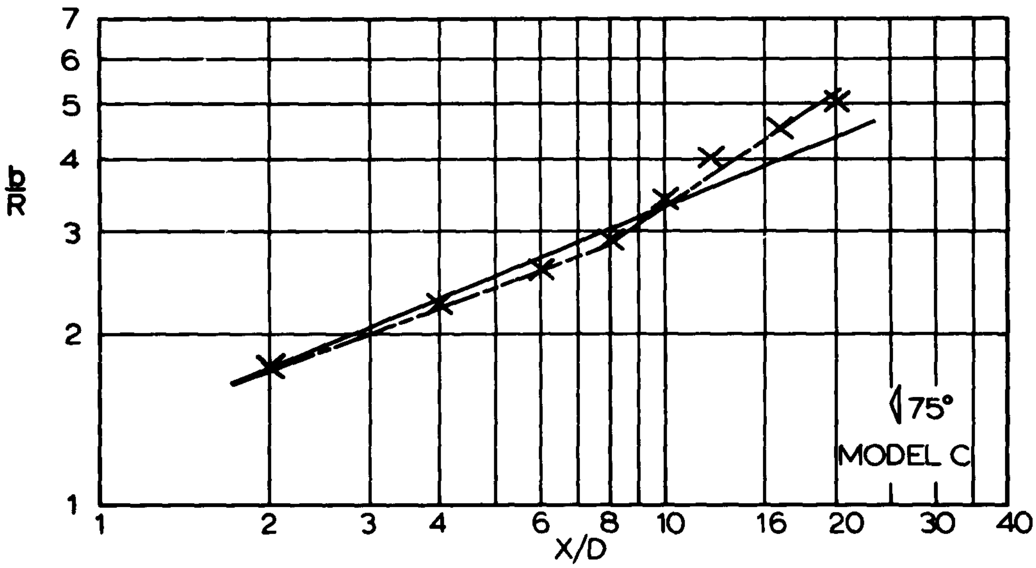


FIG A-15. EXPERIMENTAL WAKE WIDTH OF MODEL C

ONE LINE APPROXIMATION ———

TWO LINE APPROXIMATION —-—

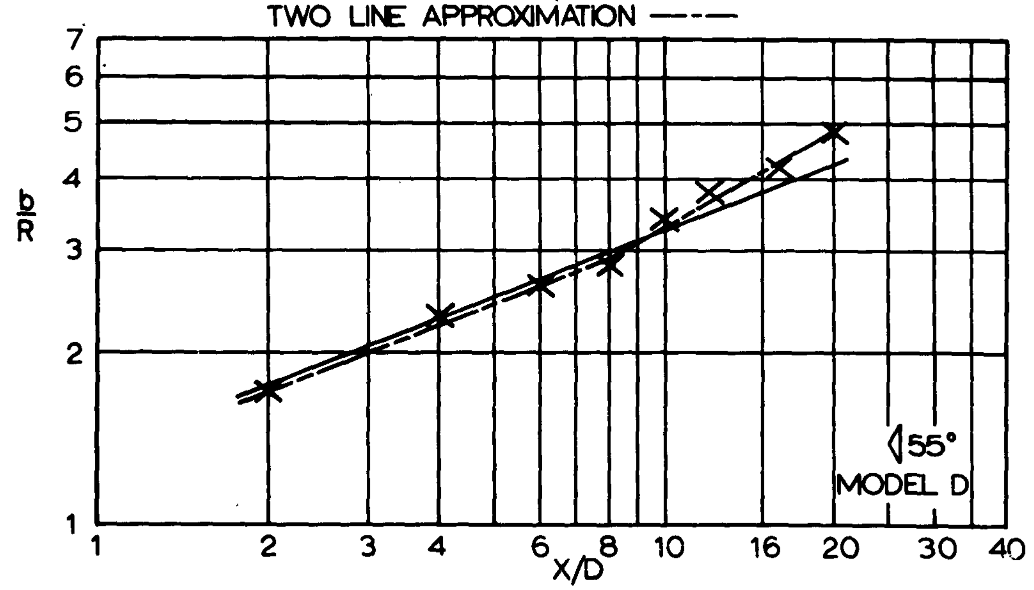


FIG A-16. EXPERIMENTAL WAKE WIDTH OF MODEL D

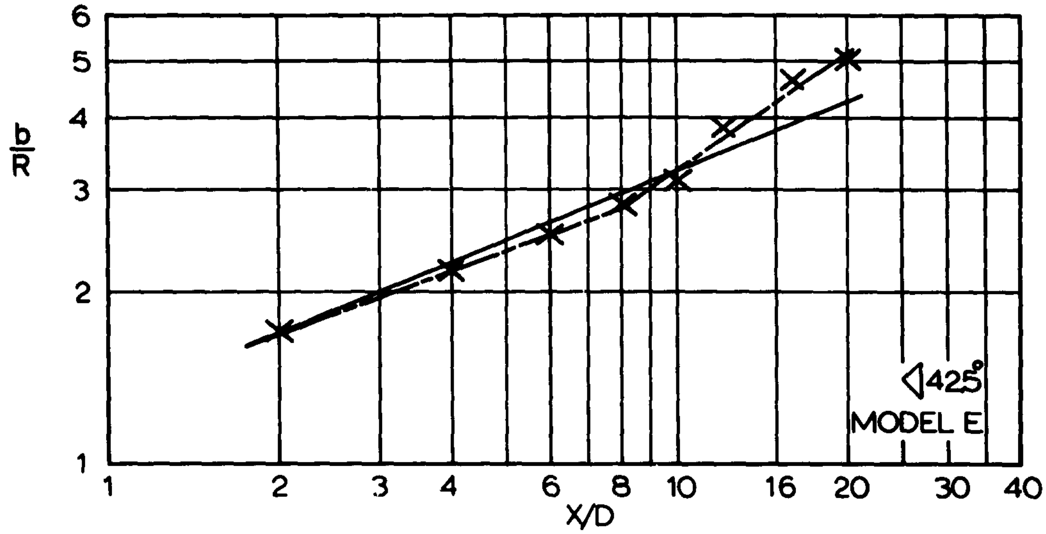


FIG A-17. EXPERIMENTAL WAKE WIDTH OF MODEL E

ONE LINE APPROXIMATION ———

TWO LINE APPROXIMATION — - —

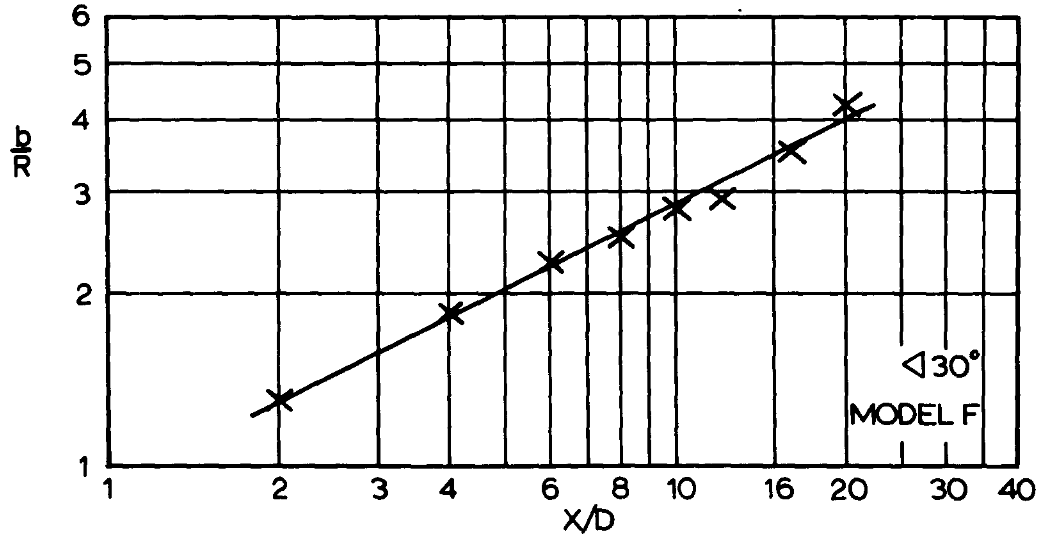


FIG A-18. EXPERIMENTAL WAKE WIDTH OF MODEL F

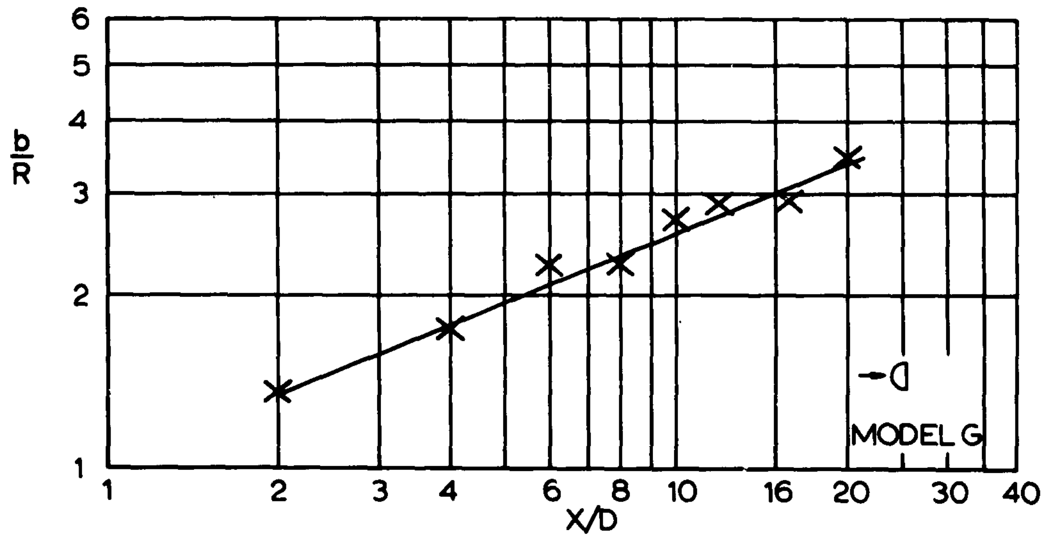


FIG A-19. EXPERIMENTAL WAKE WIDTH OF MODEL G

ONE LINE APPROXIMATION ———

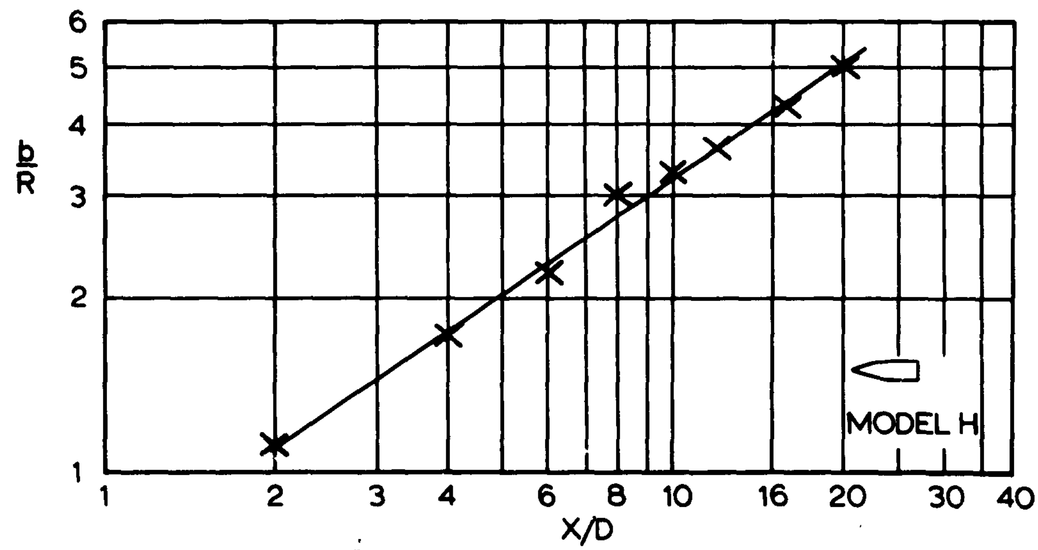


FIG A-20. EXPERIMENTAL WAKE WIDTH OF MODEL H

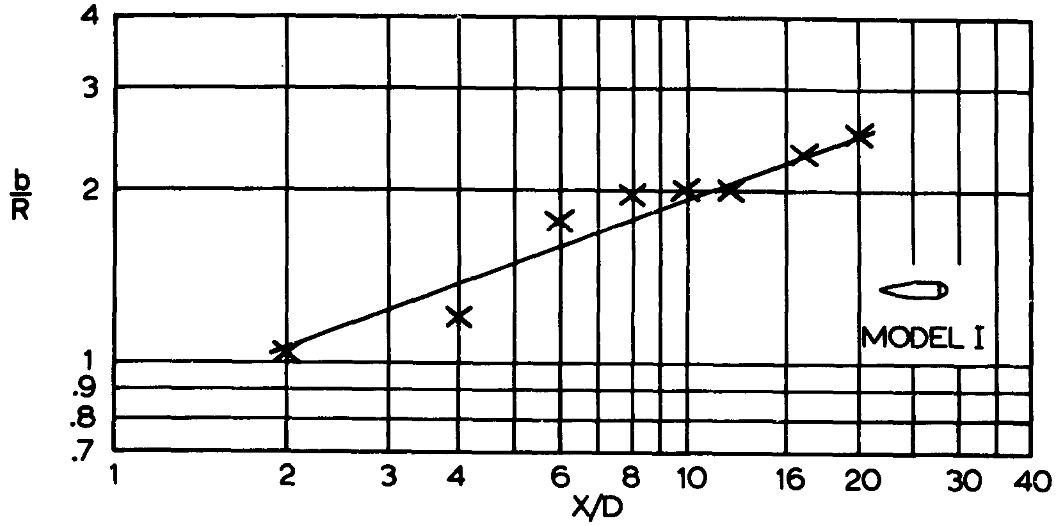


FIG A-21. EXPERIMENTAL WAKE WIDTH OF MODEL I

ONE LINE APPROXIMATION ———

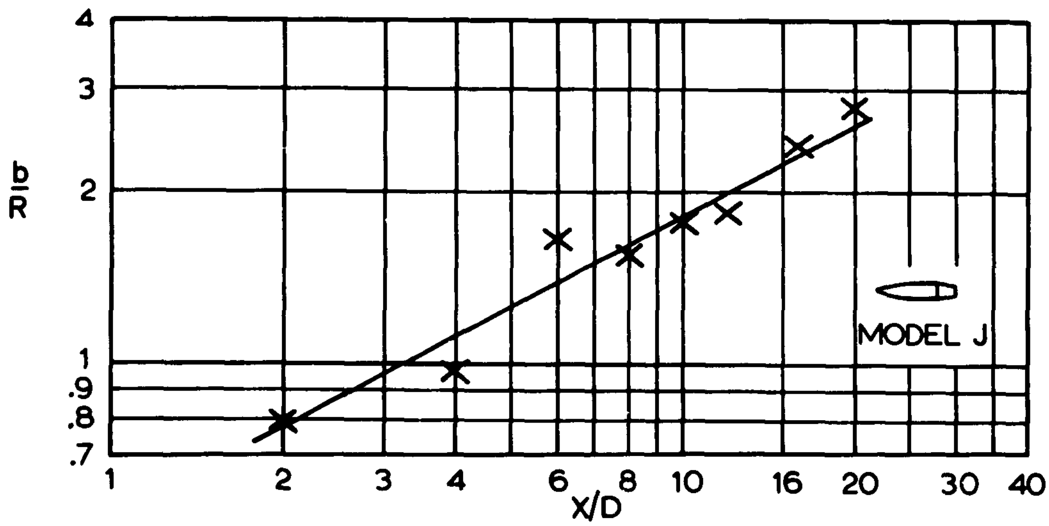


FIG A-22. EXPERIMENTAL WAKE WIDTH OF MODEL J

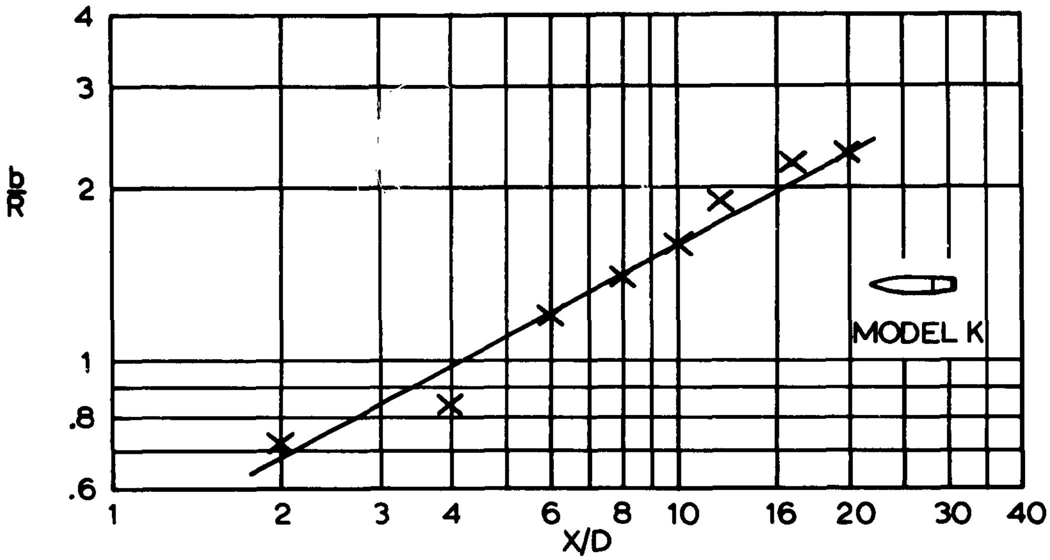


FIG A-23. EXPERIMENTAL WAKE WIDTH OF MODEL K

ONE LINE APPROXIMATION ——

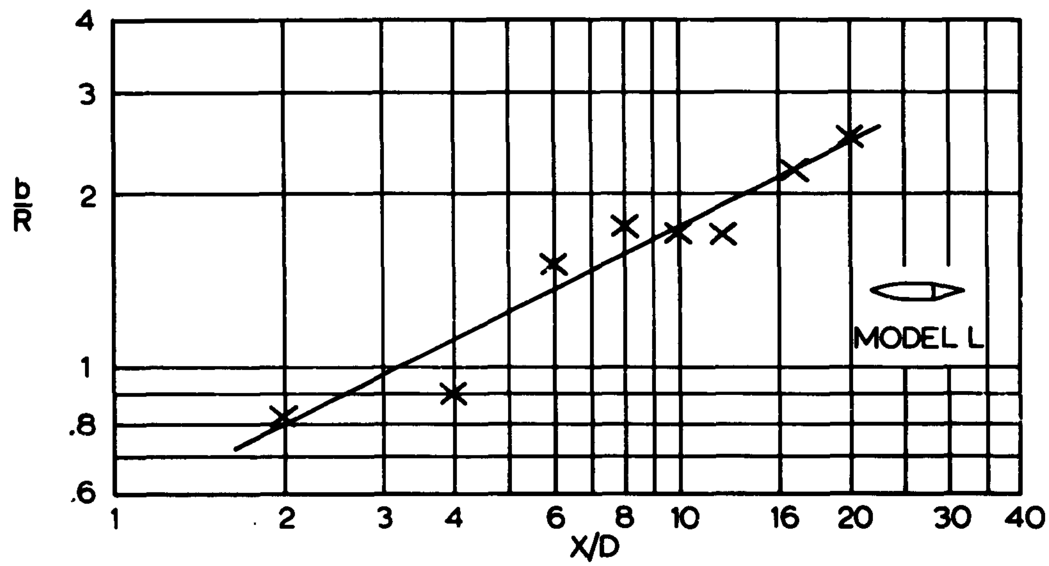


FIG A-24. EXPERIMENTAL WAKE WIDTH OF MODEL L

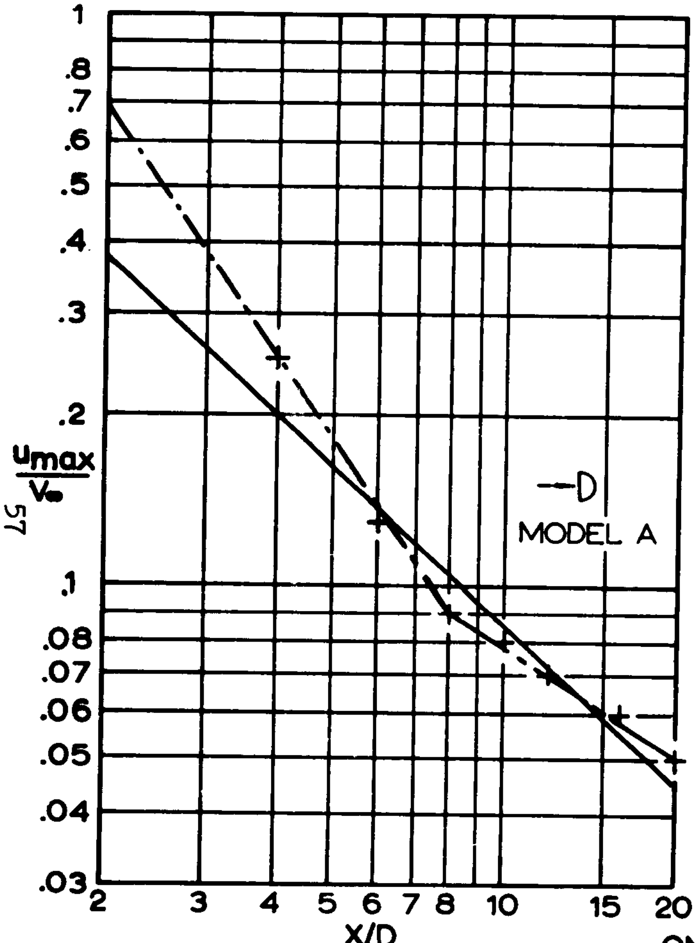
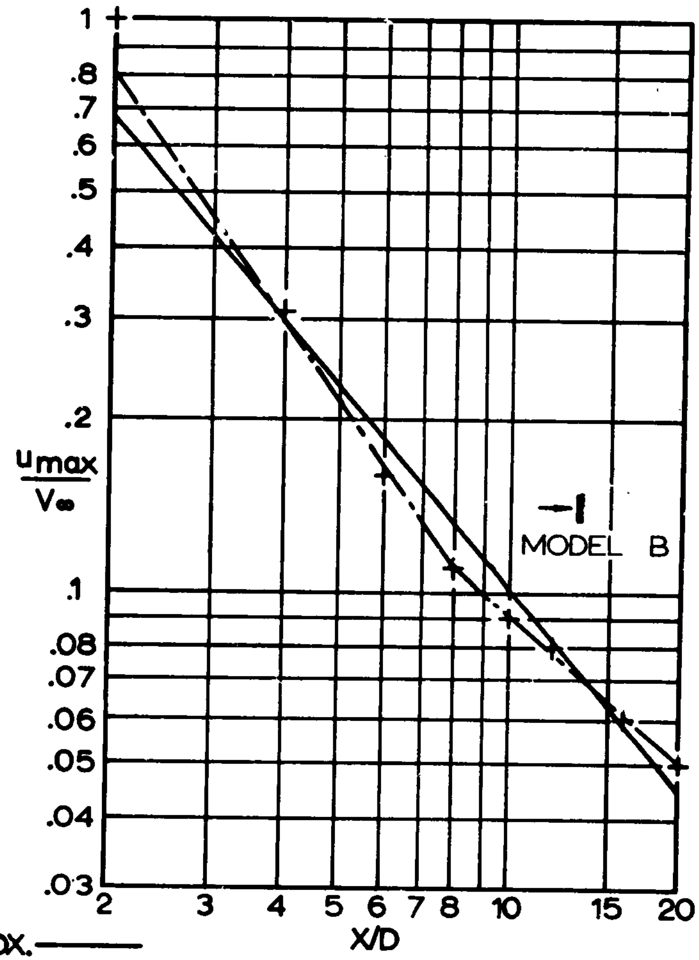


FIG A-25. CENTERLINE VELOCITY DEFECTS OF MODEL A



ONE-LINE APPROX.——
TWO-LINE APPROX.—·—

FIG A-26. CENTERLINE VELOCITY DEFECTS OF MODEL B

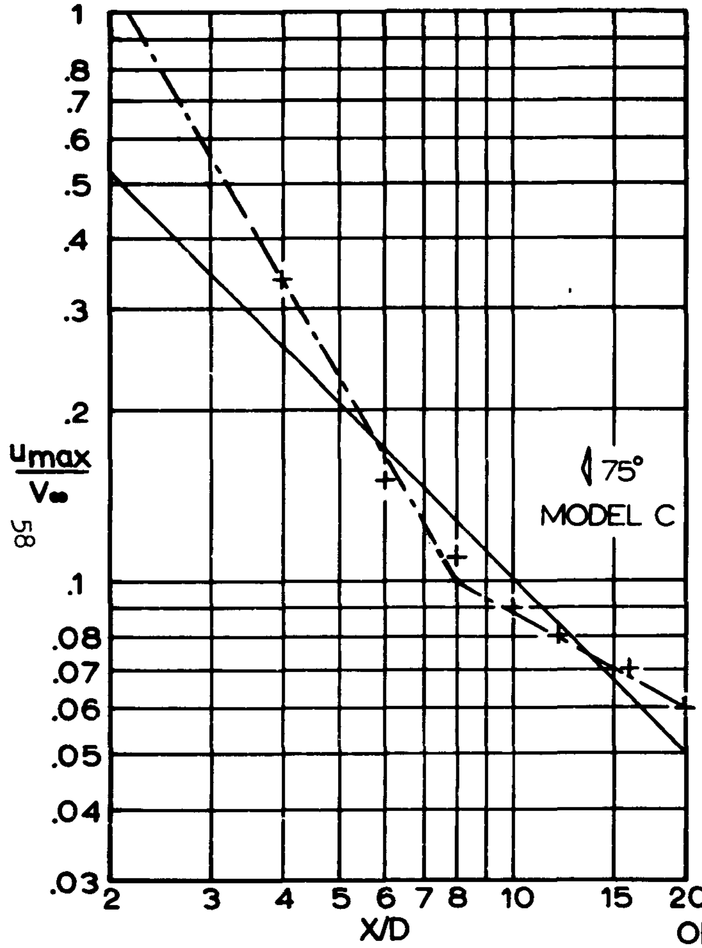


FIG A-27. CENTERLINE VELOCITY DEFECTS OF MODEL C

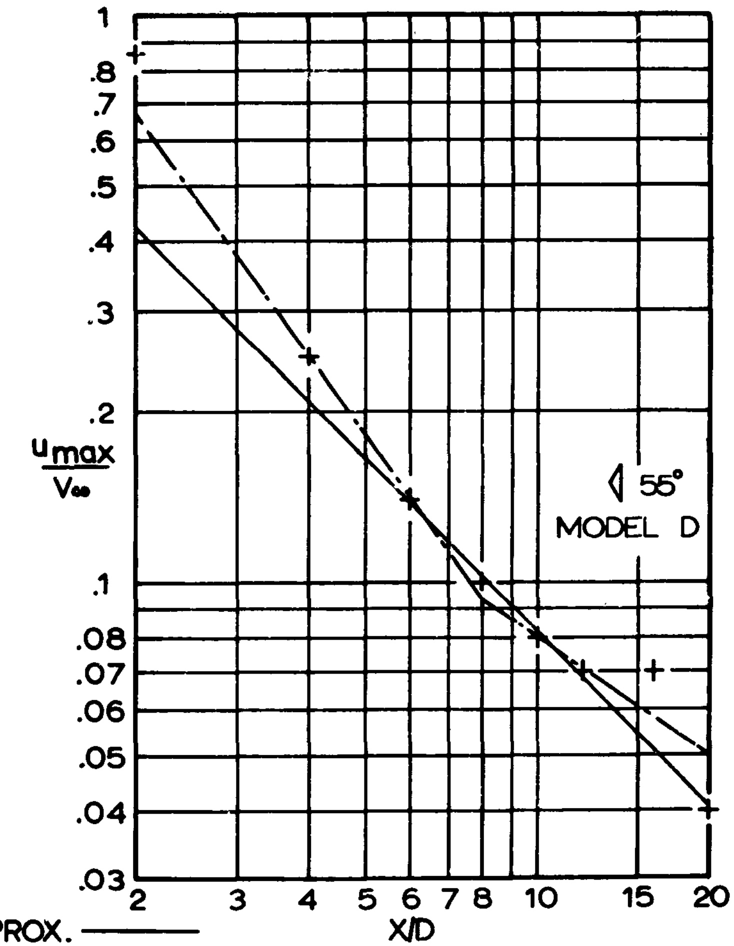
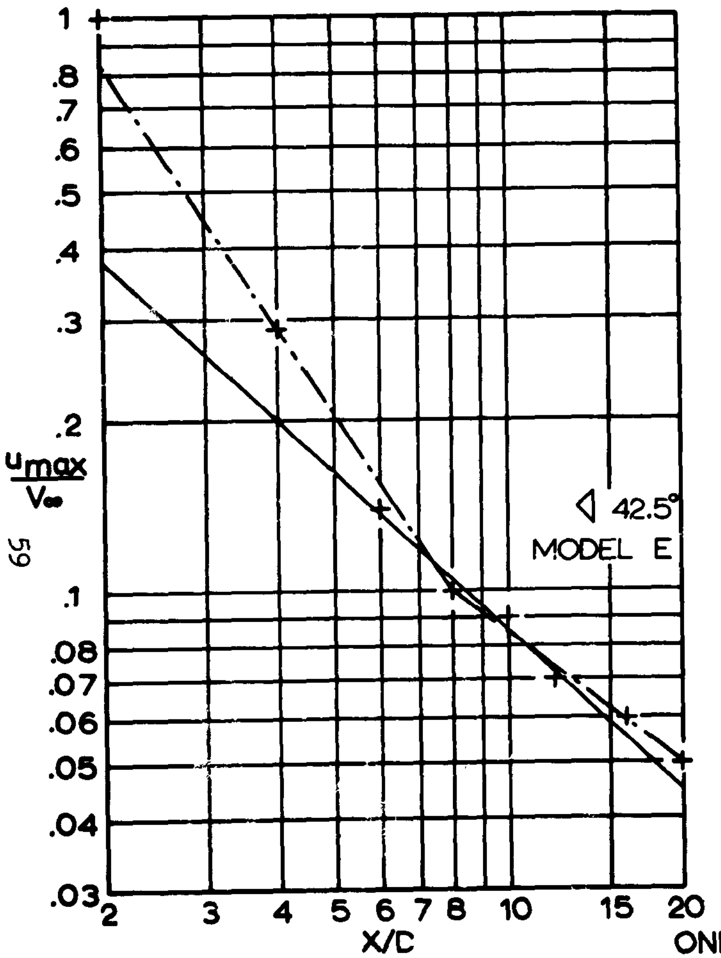


FIG A-28. CENTERLINE VELOCITY DEFECTS OF MODEL D

ONE - LINE APPROX. ———
TWO - LINE APPROX. —·—·—



ONE-LINE APPROX. ———
TWO-LINE APPROX. —-—

FIG A-29. CENTERLINE VELOCITY DEFECTS OF MODEL E

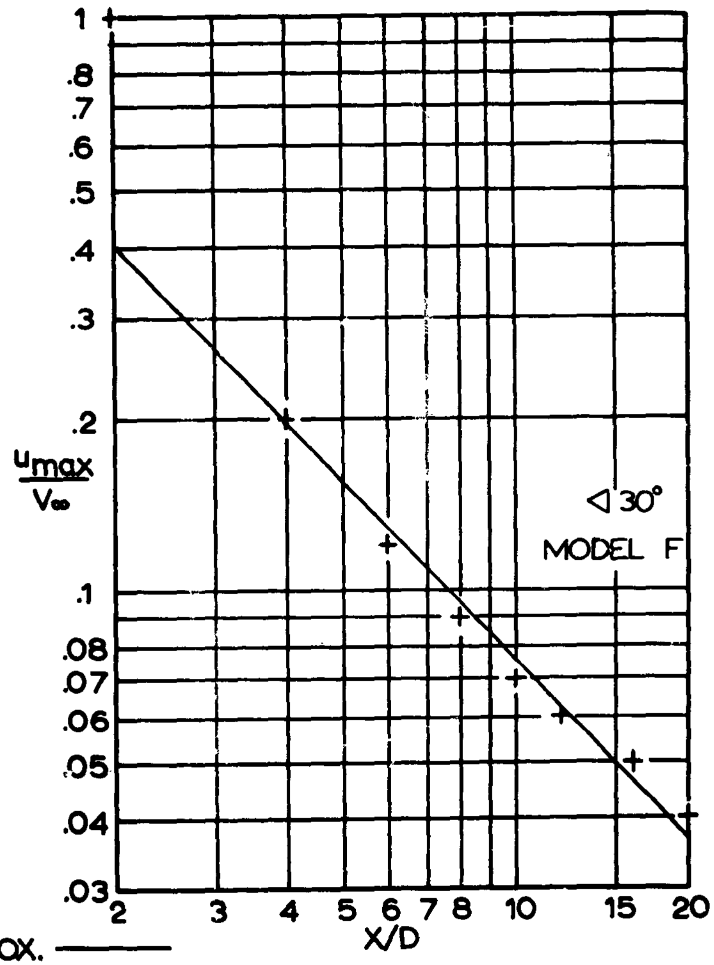
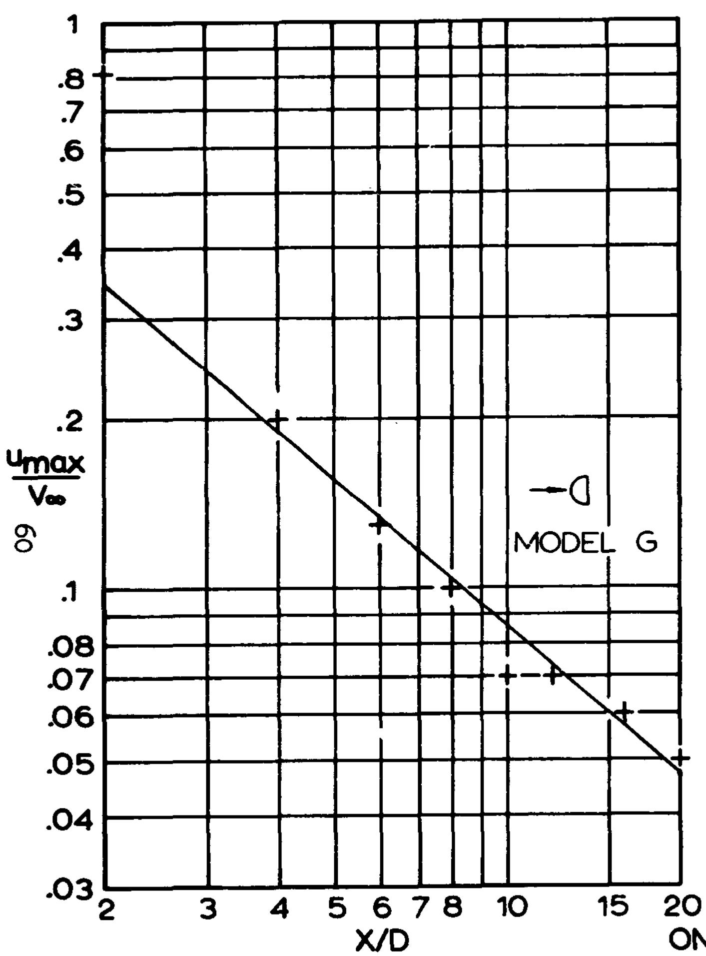
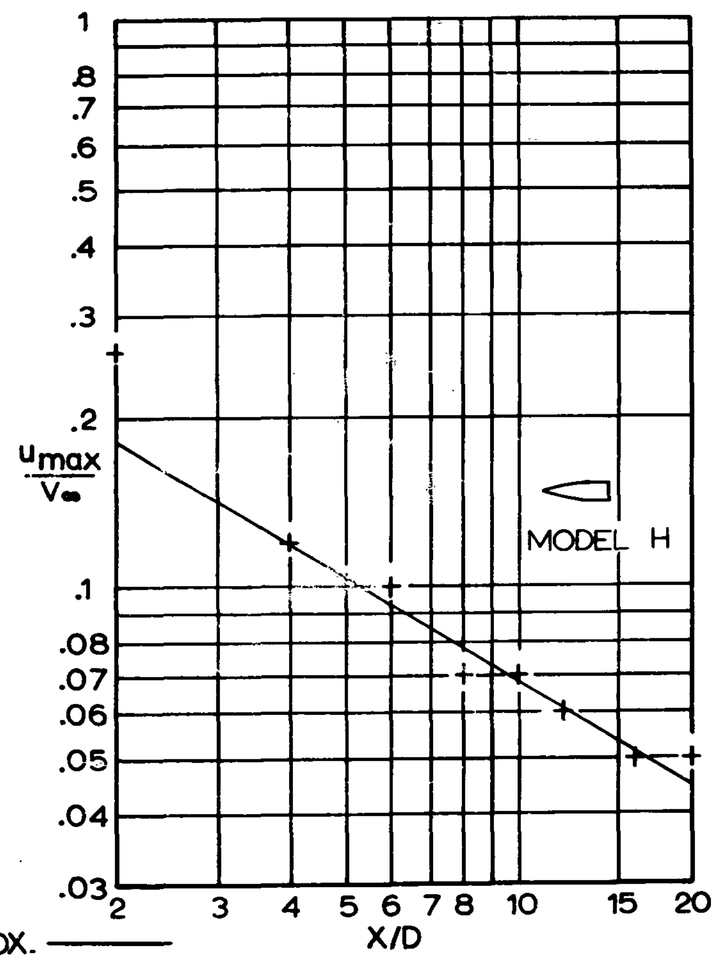


FIG A-30. CENTERLINE VELOCITY DEFECTS OF MODEL F



60



ONE LINE APPROX. ———

FIG A31. CENTERLINE VELOCITY DEFECTS OF MODEL G

FIG A-32. CENTERLINE VELOCITY DEFECTS OF MODEL H

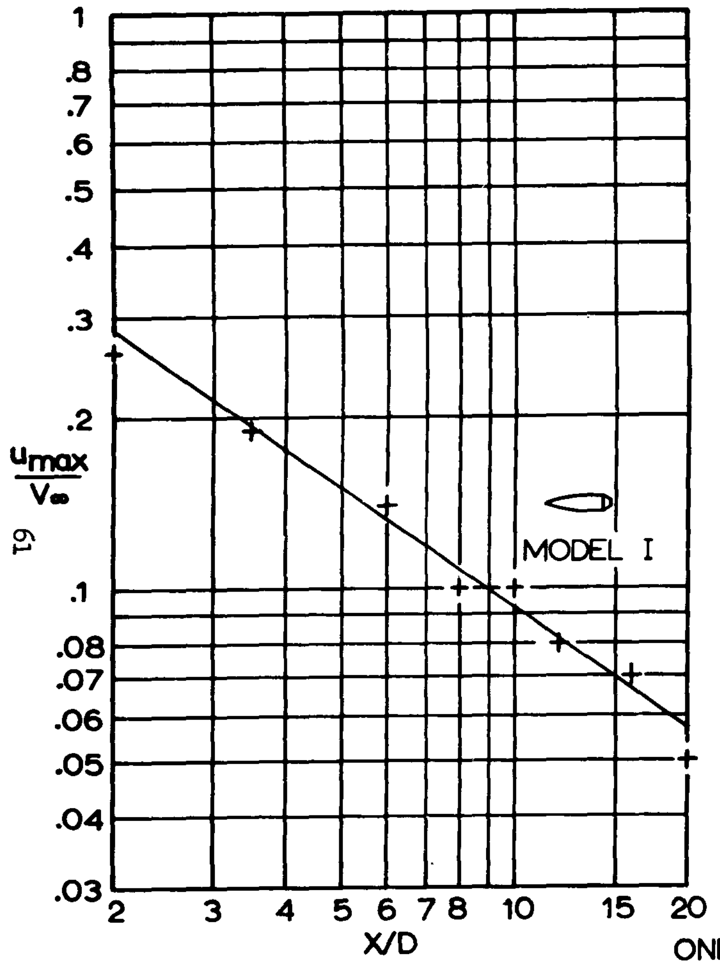


FIG A-33. CENTERLINE VELOCITY DEFECTS OF MODEL I

ONE LINE APPROX. ——

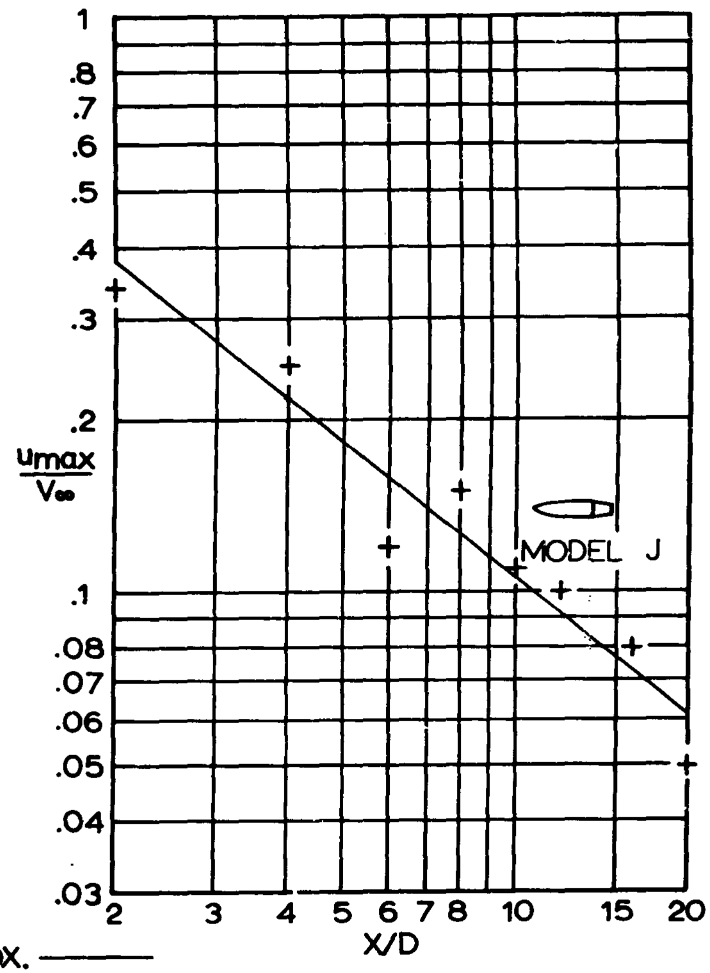


FIG A-34. CENTERLINE VELOCITY DEFECTS OF MODEL J

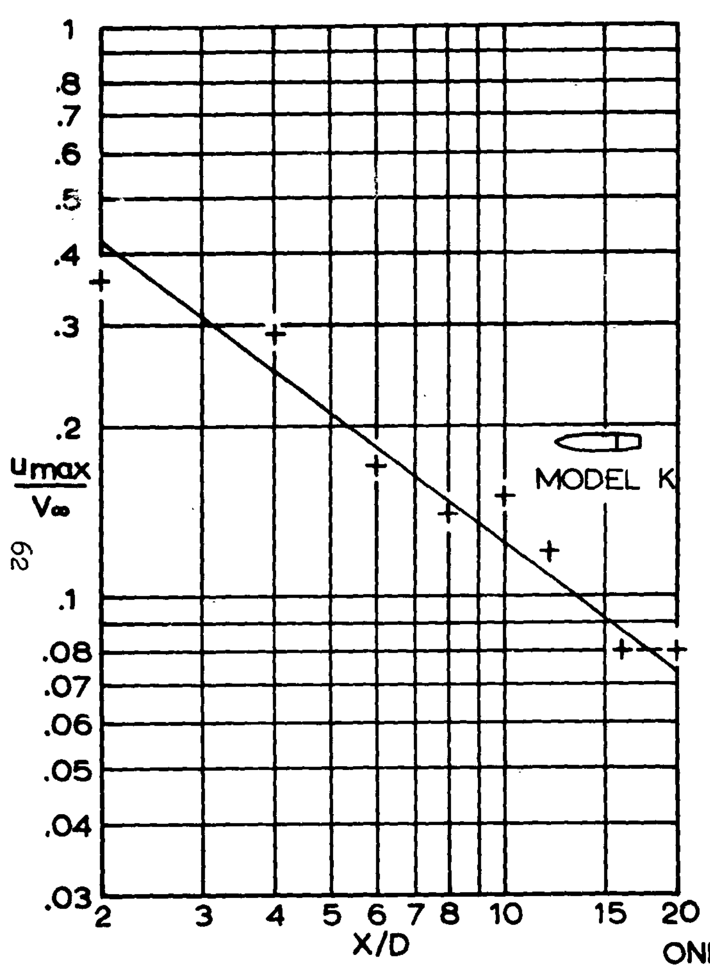


FIG A-35. CENTERLINE VELOCITY DEFECTS OF MODEL K

ONE LINE APPROX. ——

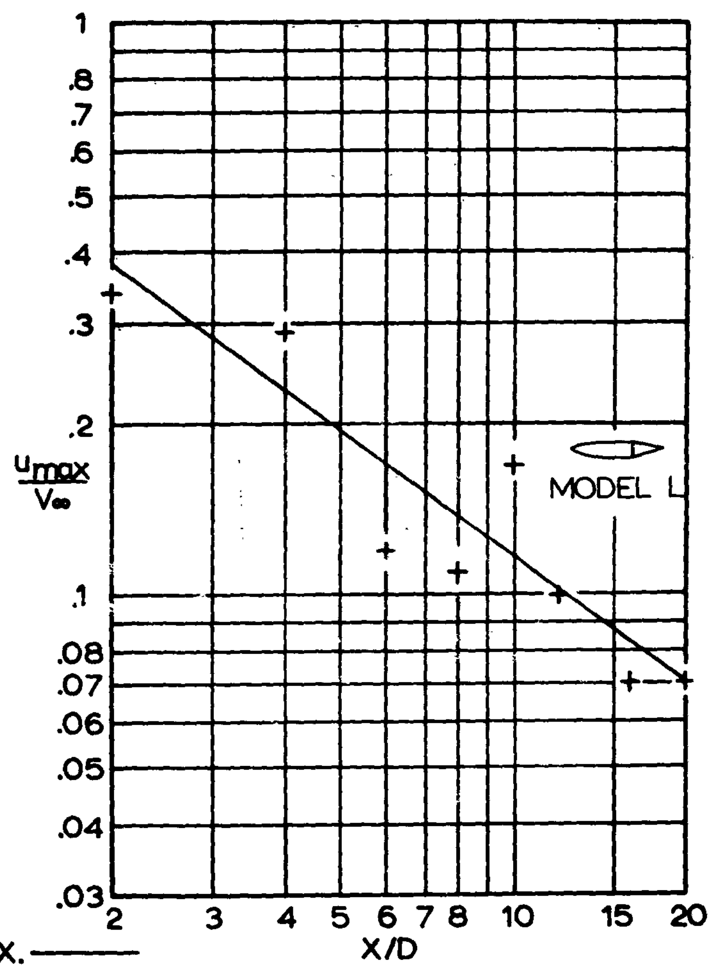


FIG A-36. CENTERLINE VELOCITY DEFECTS OF MODEL L